

AD-A225 368

# NAVAL POSTGRADUATE SCHOOL Monterey, California



## THESIS

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Co E D

NATIONWIDE MOBILE COMMUNICATION SYSTEMS

by

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Volume 3

Appendix B - D

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## APPENDIX B

### COMMUNICATION, SATELLITE, AND NAVIGATION CONCEPTS

#### A. PURPOSE

This technical exposition is limited in breadth and depth, and is presented to provide a broad overview for readers who have little or no technical background.

#### B. FUNDAMENTALS

To understand how these systems function it is first necessary to be familiar with basic electrical concepts.

##### 1. Electromagnetism

Electricity and magnetism are familiar to everyone. The effects of static electricity on a dry, wintry day, the attraction of a compass needle to the Earth's magnetic poles, and the propagation and reception of radio waves are all examples of electromagnetic phenomena.

Electromagnetic fields are a space and time-dependent pattern of energy. The analysis of electromagnetic fields, their interrelationships and their interaction with matter forms the basis of all electrical laws. These basic electrical properties form the building blocks for more complex configurations called networks or circuits. [Ref. 16:ch. 1, p. 1]

## 2. Electrical Currents

Electricity is composed of electrons moving through a substance, most typically a metal such as copper. Energy must be applied to move electrons through a conductor. Typically, this occurs by a chemical reaction in a battery, the effects of an electromagnetic field created by the conversion of mechanical energy in a generator, or sunlight interacting with a solar cell.

Voltage is a measure of the potential difference across an electrical circuit and can be thought of as pressure. Current or amperage is the amount of electrons moving through a circuit, and is analogous to volume of flow. The unit of electrical power is the watt and is equal to voltage multiplied by current.

### a. Direct Current

In considering electrical current flow, it is natural to think of a single, constant force causing electrons to move. When this is so, the electrons always move in the same direction through a path or circuit of conductors connected together in a continuous chain. Such a current is called direct current, abbreviated dc. It is the type of current furnished by batteries, solar cells, and dc generators. Dc is illustrated in Figure 119. [Ref. 16:ch. 2, p. 14]

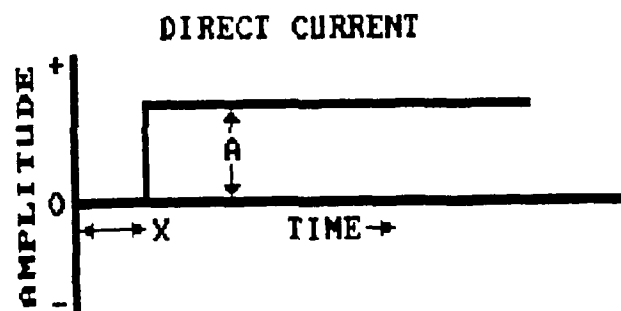
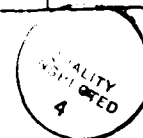


Figure 119. Direct Current

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#### b. Alternating Current

It is also possible to have a current that periodically reverses its direction of flow. This is called alternating current, abbreviated ac. The reversals (alternations) may occur at any rate from a few per second to up to billions per second. Two reversals make a cycle. The number of cycles that occur per second is called the frequency and is abbreviated Hz. Alternating currents are created by ac generators and special electrical circuits called oscillators. Alternating current makes radio communication possible.

#### c. Frequency Bands

Ac frequencies ranging from 20 to 20,000 Hz are called audio frequencies, or AF, because this is the frequency range of air vibration that humans can hear. Ac frequencies above 20,000 Hz are called radio frequencies, abbreviated as RF. Radio frequencies of up to 100,000,000,000 Hz are used in radio transmission. At higher radio frequencies, it is convenient to use a unit of frequency larger than the Hz. Three larger units are the kilohertz (KHz), equal to 1000 Hz, the megahertz (MHz), equal to one million hertz, and the gigahertz (GHz), equal to one billion hertz.

For classification purposes, ranges of frequencies are divided into bands. Figure 120 illustrates band designations and the relative location of systems within the radio spectrum. Frequency sub-bands are also designated by the letters listed in Table 31 [Ref. 52:pp. 212-213].

# Band Designation and Frequency Ranges

Relative Position  
of Communication and Navigation Systems

VLF	AUDIO FREQUENCY				10 - 30 KHz	
LF	LORAN - C		30 - 300 KHz			
MF	AM RADIO		300 KHz - 3 MHz			
HF	LONG DISTANCE AERONAUTICAL AND MARITIME MOBILE COMMUNICATIONS				3 - 30 MHz	
VHF	METEOR BURST	TV & FM RADIO	TRANSIT	TV	30 - 300 MHz	
UHF	TRANSIT ARGOS	SMR & CELLULAR	NAVIGATION & MOBILE COMMUNICATION SATELLITES		300 MHz - 3 GHz	
SHF	OMNITRACS		3 - 30 GHz			
EHF					30 - 300 GHz	

Figure 120. Band Designation and Frequency Ranges; Relative Position of Communication and Navigation Systems

TABLE 31

## LETTER BAND DESIGNATIONS

<u>Band</u>	<u>Frequency Range</u>
C	3.7-6.425 GHz
K	10.7-18 GHz
K <sub>a</sub>	18-304 GHz
K <sub>u</sub>	10.7-18 GHz
L	1.5-1.6 GHz
S	2.5-2.7 GHz
X	7.25-8.4 GHz

3. Analog

## a. Waveform Mixing

Ac is typically represented as a sine wave, as shown in Figure 121. Ac does not always take the form of a sine wave, and can assume an infinite variety waveforms. Ac waveforms are known as analog signals because they vary in a continuous manner.

Ac waveforms can be added together to form a more complex waveform. This is illustrated in Figure 122. Two waveforms added, point by point at each instant of time, will form a resultant waveform. When two waveforms at a given instant have the same direction of flow or polarity, the resulting waveform is the sum of the two. When they have opposite polarities, the resulting waveform is the difference; if one polarity component is larger, the resultant is the same polarity as that larger component.

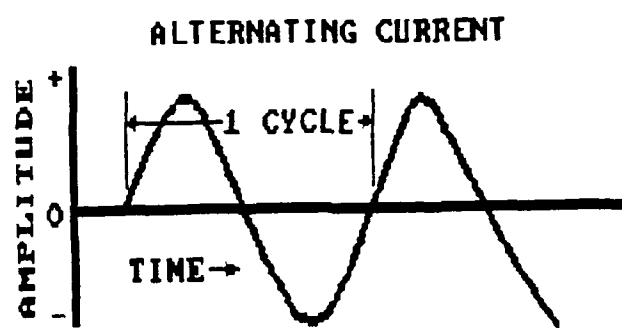


Figure 121. Alternating Current



## Addition of Waveforms

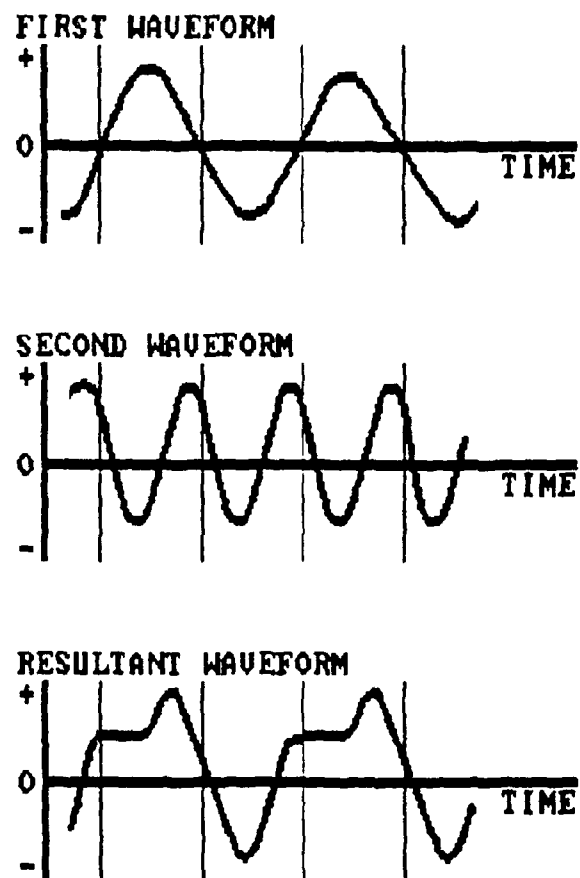


Figure 122. Addition of Waveforms

The mixing waveforms are used extensively in radio circuitry and enables the transmission of information. [Ref. 16:ch. 1, pp. 2-5]

b. Phase

The term phase essentially means time or the interval between the instant when one event occurs and the instant when a second related event takes place. In ac circuits the current and voltage amplitude (instantaneous values) change continuously, so the concept of phase or time is important. Like the mixing of waveforms, phase changes or shifts can be used to convey information.

Since each ac cycle occupies exactly the same amount of time as every other cycle of the same frequency, the cycle itself can be used as the time unit. Using the cycle as the time unit makes the specification of phase independent of the frequency of the current, as long as the frequency does not change.

The interval or phase difference under consideration usually will be less than one cycle. As shown in Figure 123, phase measurements are made in degrees, where one cycle is divided into 360 parts. The phase difference between two currents of the same frequency is the angular difference between corresponding parts of cycles. This is illustrated in Figure 124. [Ref. 16:ch. 2, p. 6]

## Phase Measurements

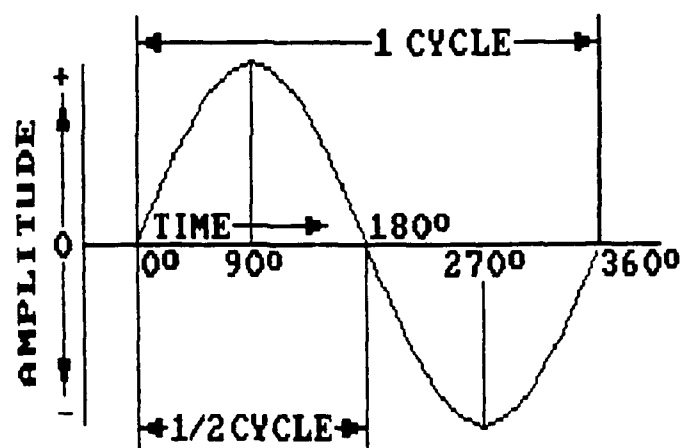


Figure 123. Phase Measurements

## Phase Differences

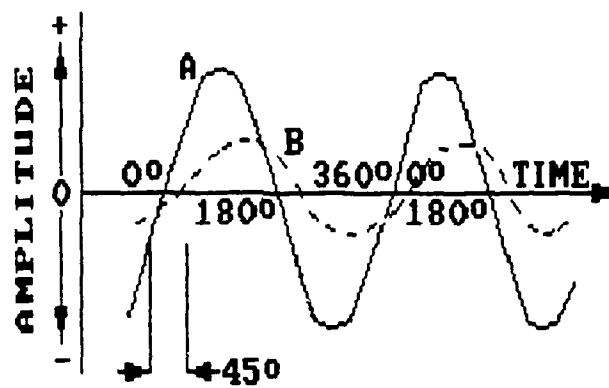


Figure 124. Phase Differences

#### 4. Digital

Unlike analog signals, where the ac waveforms vary in a continuous manner, digital waveforms can have only a finite number of states. In binary digital systems, there are only two distinct states, represented in base-2 arithmetic by the numbers zero and one. These binary digits are known as bits. The binary states described as zero and one may represent on and off or, in a communications transmission, a mark and a space. This is shown in Figure 125. Bits are usually conveyed by dc voltage levels. Because it is not always possible to achieve exact voltages, digital circuits consider the signal to be a zero or a one if the voltage comes within certain bounds, as illustrated in Figure 126. [Ref. 16:ch. 8, p. 1]

Multiple sequences of bits must be grouped together to provide more than two values. Commonly, eight bits are grouped together to form a byte. A byte can represent one of 256 values ( $2^8$ ). Bytes can also be combined to represent a greater number of values. Byte sequences are used to convey information, such as numbers or letters, and instructions to digital circuits.

In digital circuits, a combination of binary inputs results in a specific binary output or combination of outputs. These circuits are used to implement digital devices ranging from simple switches to supercomputers. [Ref. 16:ch. 8, p. 1]

## Binary States

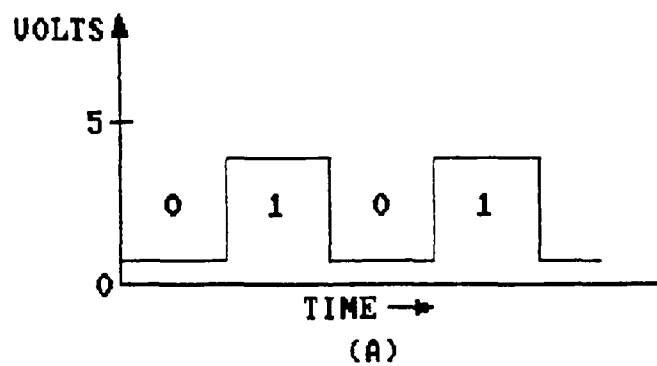


Figure 125. Binary States

## Binary State Voltage Levels

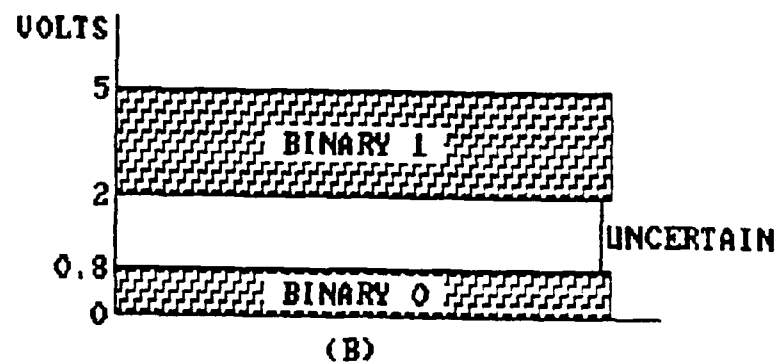


Figure 126. Binary State Voltage Levels

## 5. Building Blocks of Radio Communications Systems

### a. Amplifiers

An amplifier is an electronic circuit that increases the power of an input analog or digital waveform. Amplifiers are designed to reproduce the input waveform with very low distortion. Amplifiers rely on various devices such as transistors, tubes, and integrated circuits to perform their power-increase function. There are many different types of amplifiers and their use depends primarily on application and frequency range. Audio frequency (AF) amplifiers are designed to operate in the frequency range of 20 to 20,000 Hz, while radio frequency (RF) amplifiers function in the frequencies above 20,000 Hz. RF power amplifiers are used to boost the output power of a transmitter before the signal is sent to the antenna.

### b. Oscillators

An oscillator is a special type of low-power amplifier that generates alternating current at a specific frequency or over a range of frequencies. The tube, transistor, or integrated circuit in the oscillator amplifies the ac signal applied to its input just as any amplifier does. The basic difference between an amplifier and an oscillator is that an oscillator feeds a portion of its output through a tuned circuit back into the input. A tuned circuit allows only a narrow range of frequencies to pass through, and blocks all other frequencies. Changing the values of the tuned



circuit controls the oscillator frequency. This process is called positive feedback or regeneration.

The input to the oscillator amplifier can come from several types of circuitry.

(1) Crystal Oscillators. One method is to apply a current across a specially-ground quartz crystal to generate an oscillation which is then fed into the amplifying stage of the oscillator. This type of oscillator functions on only one frequency. Each additional frequency requires an additional crystal. A crystal oscillator circuit may be modified to operate over a very limited frequency range with addition of extra components. This type of oscillator is called a variable frequency crystal oscillator (VXO). The primary advantage of crystal oscillators is their simplicity and frequency stability. Common devices which use crystal-controlled oscillators include automatic garage door opener transmitters and inexpensive citizens-band (CB) walkie-talkies. [Ref. 16:ch. 10, pp. 1-4]

(2) Variable Frequency Oscillators. A variable frequency oscillator (VFO) is tunable over a wider range of frequencies than the VXO. Here, the input oscillation comes from a capacitor and inductor circuit instead of a quartz crystal. The capacitor and inductor function together, or resonate, to allow only a very narrow range of frequencies to pass through them and into the amplifier. The oscillator output frequency is changed by varying either the value of the

capacitor or the inductor. The advantage of this oscillator is that it is capable of covering a range of frequencies which would otherwise require many separate crystal oscillators. The major drawback of a VFO is its lack of frequency stability and accuracy. [Ref. 16:ch. 10, pp. 4-8]

VFOs are used in low-cost transistor radios. Rotating the tuning knob changes the value of the capacitor in the tuning circuit. This changes the frequencies allowed to pass further on into the radio circuitry.

### c. Frequency Synthesizers

Like oscillators, frequency synthesizers are circuits which are designed to produce RF output at a desired frequency. In a synthesizer the output signal is a function of the input. This input may come from electrical logic signals or mechanical switches. Synthesizers tend to be much more complicated than oscillators.

The range of frequencies from synthesizers varies according to application. The smallest frequency change that can be accommodated is called the resolution. Usually the resolution is in steps of a power of ten. The major attribute of synthesizers is frequency accuracy and stability. Synthesizers are in some manner locked on to the frequency of a crystal oscillator. The synthesizer's frequency stability is determined by the stability of the crystal oscillator. [Ref. 16:ch. 10, pp. 8-9]

(1) Direct Frequency Synthesis. Direct synthesis is accomplished by mixing the output of one or more oscillators to produce a new frequency. The number of frequencies, or channels, that are available is dependent on the type of oscillator circuitry and number of crystals used. A drawback of direct synthesis is that the synthesizer frequency accuracy and stability are a function of the accuracy of each crystal. Also, the cost and physical space required by multiple crystals and the related circuitry can be relatively expensive. The older 23-channel citizens-band radios used direct frequency synthesis. [Ref. 16:ch. 10, pp. 9-10]

(2) Indirect Synthesis. Indirect synthesis uses a circuit called a phase-locked loop (PLL). The description "indirect" refers to the method of generating the output frequency by stabilizing a voltage-controlled oscillator (VCO). A VCO operates similarly to a variable frequency oscillator, except that a device called a varactor diode is used in place of the variable capacitor. The capacitance of a varactor diode is changed by varying the voltage applied to it.

Five elements make up the phase-lock loop: a VCO, a programmable divider, a phase detector, a loop filter, and a reference frequency source. This is shown in Figure 127.

## Phase - Lock Loop

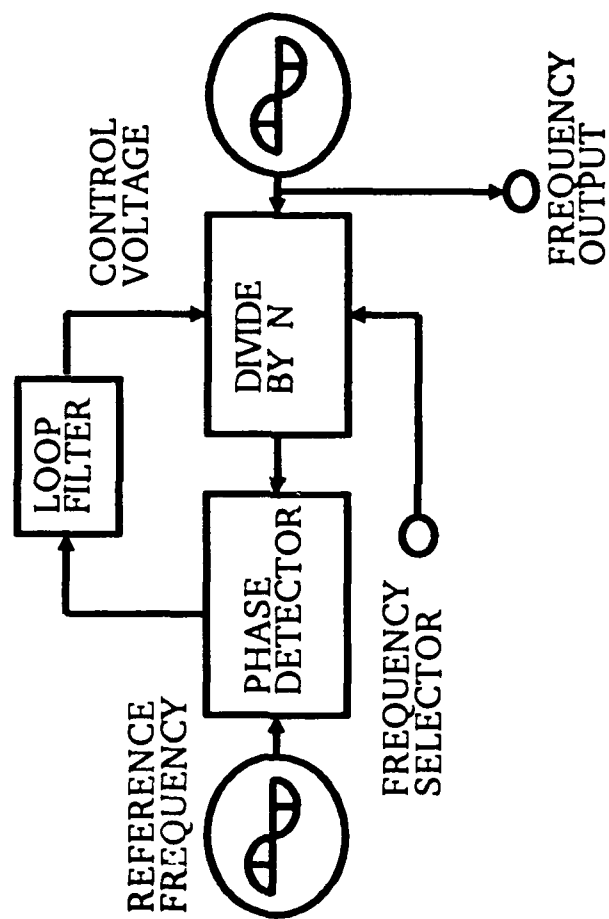


Figure 127. Phase-Lock Loop

A PLL synthesizer is "programmed" by an external source to generate a particular frequency. The desired frequency is input into the programmable divider. The PLL operates by taking the signal from the VCO, dividing this frequency by a number stored in the programmable digital divider, and comparing this frequency to a precise and stable reference frequency in a phase detector. The phase detector produces an electrical output that indicates a positive or negative phase difference between the VCO output and the reference oscillator. The phase detector output is fed back into the VCO through a filtering circuit which removes any extraneous signals that would adversely affect the operation of the VCO. The loop quickly adjusts the output of the phase detector to zero. When the output of the phase detector reaches zero the output of the programmable divider is equal to the reference frequency. The advantage of a PLL synthesizer is that it can be designed to cover a very wide range of frequencies with high resolution, and by using integrated circuits requires less components than direct synthesis. The advent of low-cost integrated circuits have made PLL synthesizers relatively inexpensive. PLL synthesizers are used extensively in consumer electronics to provide digital tuning of radios and television sets. [Ref. 16:ch. 10, pp. 11-13]

#### d. Frequency Multipliers

Oscillators and synthesizers may have good frequency stability when operated at lower frequencies, but at higher frequencies this is often not true. A frequency multiplier circuit solves this problem by multiplying the oscillator or synthesizer output frequency two, three, four or five times. The stability and frequency output is always an exact multiple of the oscillator or synthesizer. Frequency multiplier stages are commonly found in communications systems operating at HF and higher frequencies. [Ref. 16:ch. 11, pp. 4-5]

#### e. Mixers and Modulators

As mentioned above, analog waveforms can be combined together to form a resultant waveform. As illustrated in Figure 128, when two signals at different frequencies are combined in a mixing circuit, the resulting output will contain each of the original input frequencies and signals at their sum and difference frequencies. These four output signals are sent into a tuned circuit which allows only one signal to pass through. Various types of mixers are used, depending on the application. Mixers which are used to combine information to be transmitted along with the transmitter primary waveform, known as the carrier, are generally known as modulators. [Ref. 16:ch. 9, p. 1]

## Frequency Mixing

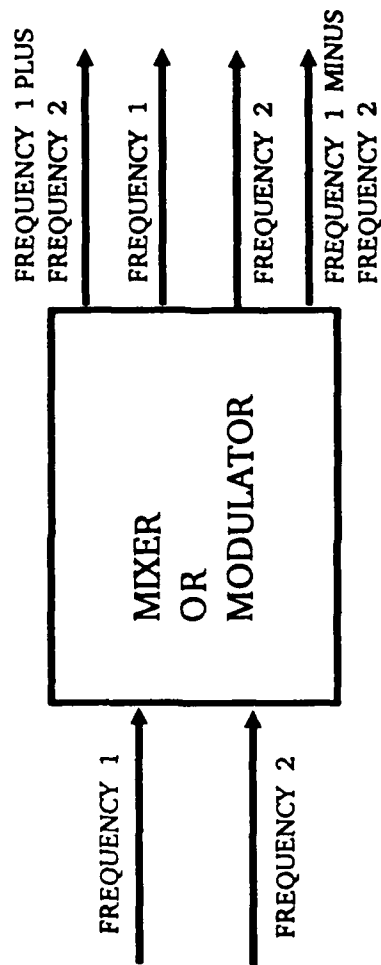


Figure 128. Frequency Mixing

f. Antennas

The antenna is a physical device used for transmitting and receiving electromagnetic radiation. Radio frequency current from a transmitter causes the electrons in the antenna to move rapidly back and forth. This generates electrical and magnetic fields which together form an electromagnetic wave that radiates from the antenna. When this electromagnetic wave sweeps across the receiving antenna it sets electrons into motion and causes weak electrical currents to flow. These currents have the same frequency and waveforms as the electromagnetic waves striking the antenna.

Although antennas are physical devices constructed primarily of metal, at radio frequencies they exhibit characteristics similar to a network of electronic components. Antennas are integral parts of the transmitter and receiver, and must be carefully designed to operate efficiently. In general, the higher the operating frequency, the more critical the design tolerances.

Omni-directional antennas send and receive with equal performance over a 360-degree range. Directional antennas exhibit gain, or the ability to concentrate their transmitted and received energy in a general direction, usually over an arc of 90 degrees or less. This has the effect of increasing the relative transmitter power and the received signal to background noise ratio.



g. Radio Wave Propagation

Figure 129 illustrates the ways in which radio waves travel.

(1) Ground Waves. Ground waves are the portion of radiated energy which follows the surface of the earth. Low-frequency (long wavelength) radio waves propagate by ground wave for hundreds or thousands of miles. As frequency increases, the ground wave will travel over shorter distances because its energy is more easily absorbed by the surface of the earth.

(2) Direct Waves. Direct waves travel the general line of sight between the transmitter and the receiver.

(3) Sky Waves. The atmosphere above 60 miles is quite thin, and radiated energy from the sun ionizes the widely-spaced air molecules. This region, known as the ionosphere, is capable of refracting, or bending, radio waves. This permits signals which are radiated towards space to be bent back towards the earth. The amount of refraction is dependent on many variables, such as solar activity (the solar flux), time of day, season of the year, and the frequency and angle of the transmission. These refracted signals are known as sky waves, and permit long-distance communication over thousands of miles.

Sky waves generally occur from 500 KHz to 30 MHz. Signals between 30 and 100 MHz are occasionally

## Radio Wave Propagation

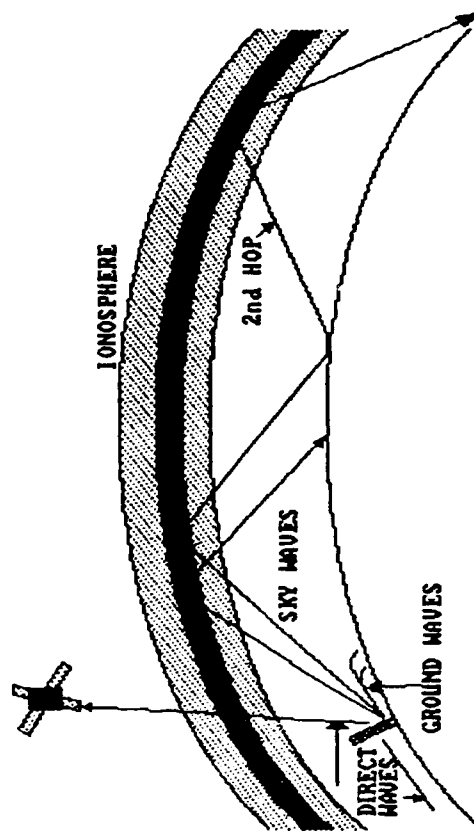


Figure 129. Radio Wave Propagation

refracted, but are considered unreliable for long-distance communication. Signals above 100 MHz are rarely refracted. [Ref. 16:ch. 22, pp. 1-8]

Figure 130 illustrates the daily and seasonal HF propagation over a Monterey, California to Washington, D.C. path.<sup>1</sup> Figure 131 also illustrates how HF propagation varies over different paths at the same time.<sup>2</sup>

(4) General Frequency Usage. Low frequencies are used primarily for their ability to propagate by ground wave over long distances. Various long-range radionavigation systems, such as the 100 KHz Loran-C system, make use of the low frequency band. Medium frequencies, such as the AM broadcast band, use ground wave to provide coverage up to several hundred miles. Frequencies from three to 30 MHz are used primarily for long distance communication via sky wave. Direct wave propagation is generally used above 30 MHz.

#### 6. Basics of Radio Communications

A transmitter in its simplest form consists of an oscillator to generate an alternating current at the required transmission frequency, a modulator to superimpose the information to be conveyed on the oscillator output (known as a carrier), one or more amplifiers to boost the modulated

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<sup>1</sup>Generated using "BandAid" HF propagation prediction software.

<sup>2</sup>Generated using "Muf Map" propagation prediction software.

# HIGH FREQUENCY PROPAGATION OVER A 24 HOUR PERIOD

TARGET: WASHINGTON DC - WASHINGTON DC (USA)      A-INDEX: 12  
 BEARING: 70 degrees      DISTANCE: 2494 miles      DATE: 07/01      FLUX: 175  
 Ionospheric Conditions: High Normal

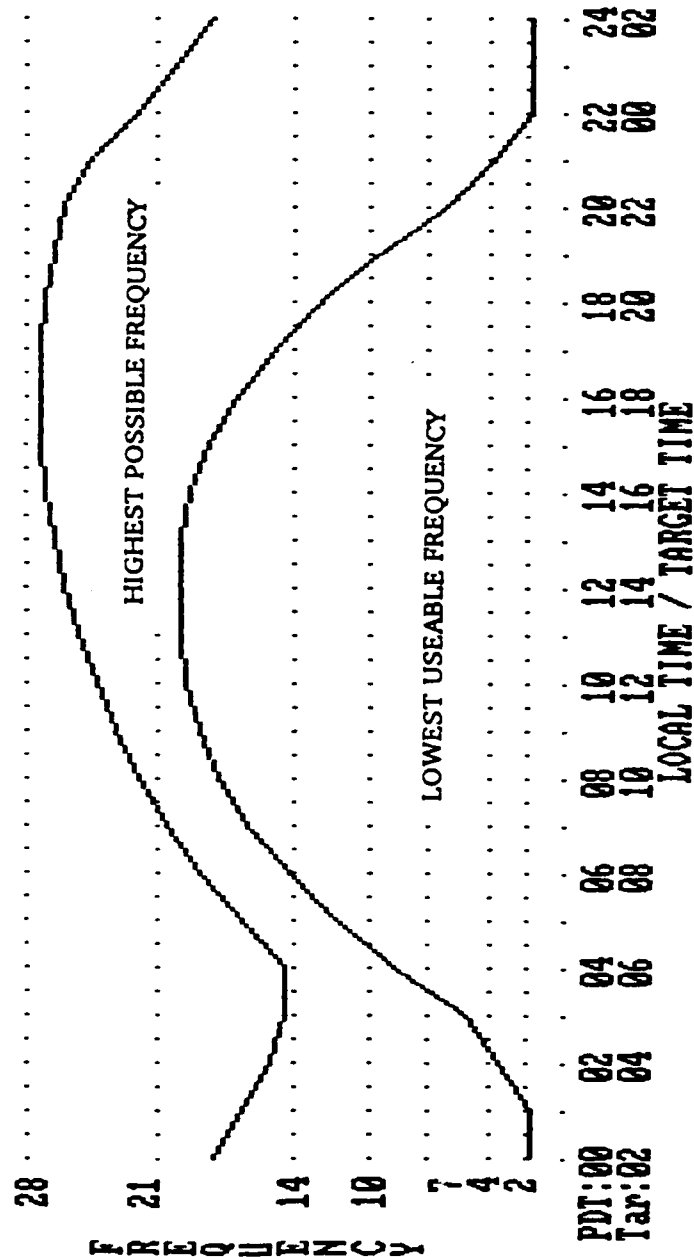


Figure 130. High Frequency Propagation Over a 24-Hour Period

# WORLDWIDE HIGH FREQUENCY PROPAGATION FROM MONTEREY, CA

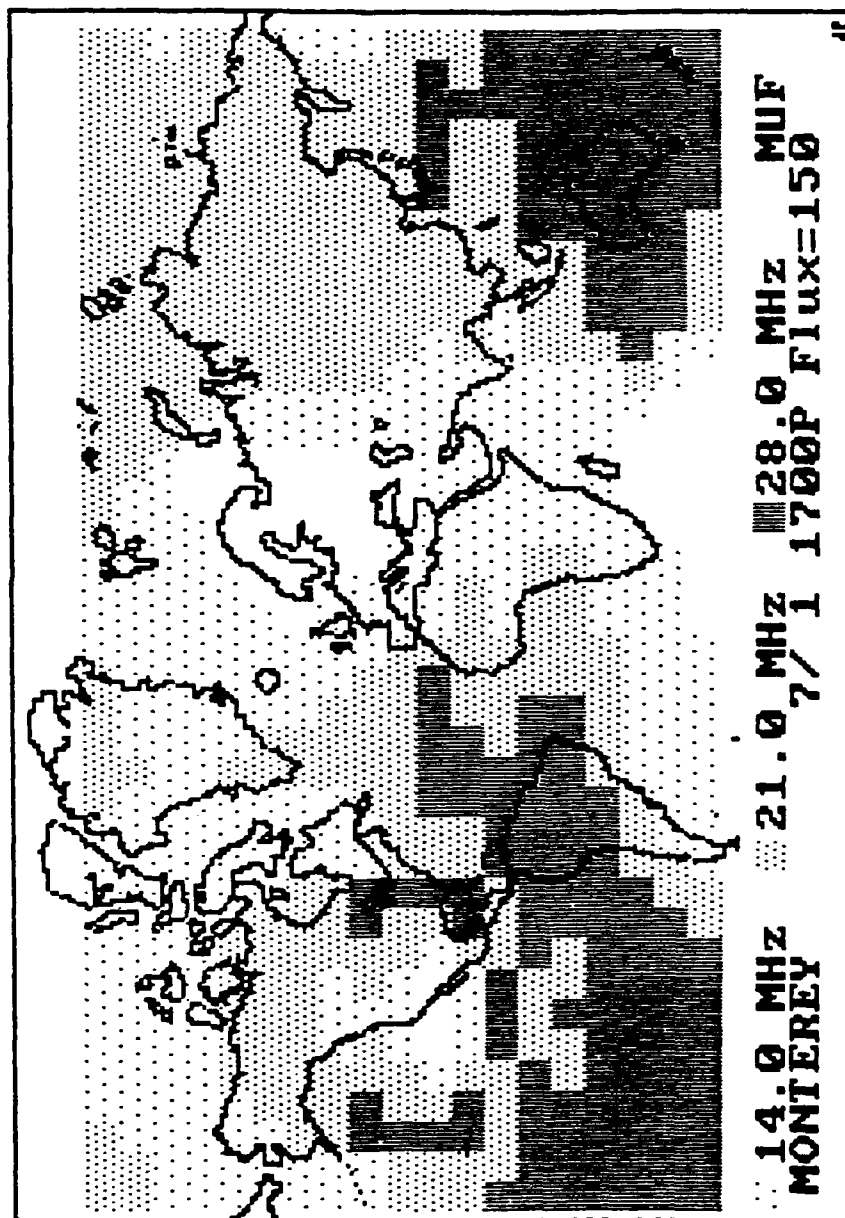


Figure 131. Worldwide High Frequency Propagation from Monterey, CA.

signal to the desired power level, and an antenna to radiate the electromagnetic energy.

In a simplified receiver, the weak currents from the antenna are amplified and processed through a mixer and tuner. The desired frequency is selected and sent to a circuit known as a detector or demodulator. This circuit separates the modulated information from the carrier. The information output is further amplified before being sent to a speaker or other circuitry.

a. Commonly Used Types of Modulation

As mentioned above, modulation is the process of varying a characteristic of a carrier wave in accordance with the signal to be conveyed. Demodulation is the process of recovering the original modulation signal from a modulated carrier wave. In the simplest of transmitters, information is sent simply by turning the transmitter on and off in a coded sequence. Early radio transmitters used the Morse Code in this manner. These are known as continuous wave (CW) transmitters because the oscillator's alternating current wave form is not modified in any manner, just switched on and off.

Many other more efficient methods exist for conveying information via radio. Instead of turning the transmitter on and off, these techniques involve changing the transmitter's RF waveform in some manner. These methods are capable of carrying voice (analog) and digital information, although some are better suited for certain applications.

(1) Double Sideband Amplitude Modulation (DSB AM). As illustrated in Figure 132, in DSB AM the carrier is mixed directly with the information to be conveyed. This produces a composite signal consisting of: (1) the carrier, (2) a signal which has a frequency equal to the difference between the modulating signal and the carrier, called the Lower Sideband (LSB), and (3) a signal which has a frequency equal to the sum of the modulating signal and the carrier, called the Upper Sideband (USB). The amplitude of the upper and lower sidebands also varies, while carrier remains constant. Next to CW, this is the simplest type of transmitter. [Ref. 16:ch. 9, pp. 2-3]

DSB AM is also the easiest signal to demodulate. The received AM signal is passed through a detection circuit which uses the carrier and only one of the sidebands to recreate the original information. The demodulated intelligence is equal to the difference in frequency between the carrier and the sideband. The amplitude (loudness) of the intelligence is proportional to the amplitude of the sideband.

This type of modulation and detection is used in commercial AM radio. While DSB AM modulation and detection may be electronically easy, it does have several limitations. Two sidebands are created, yet only one is necessary to convey the intelligence. The six KHz to ten KHz-wide AM signal uses up twice as much spectrum as is required to convey the

## Amplitude Modulation

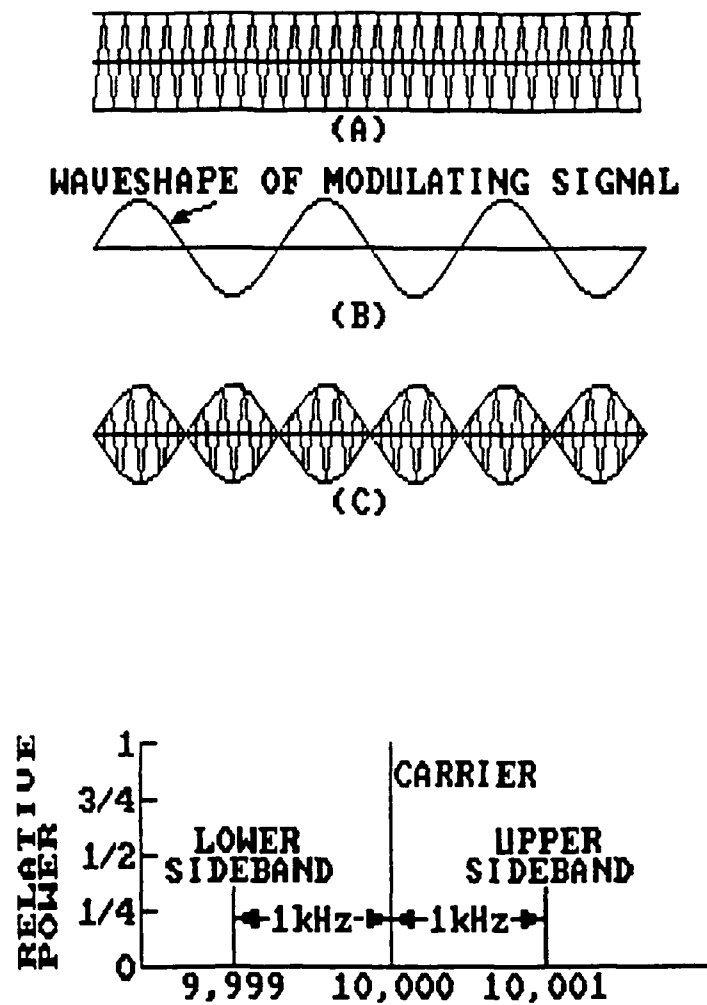


Figure 132. Amplitude Modulation



information. The carrier conveys no intelligence, but consumes about two-thirds of the transmitter's power. [Ref. 16:ch. 18, pp. 1-2]

(2) Single Sideband (SSB). SSB overcomes these difficulties by removing the carrier and one sideband prior to sending the signal to the RF power amplifier. This enables all the transmitter's power to be contained in the sideband, and cuts the required bandwidth in half. The signal is demodulated at the receiver by replacing the missing carrier at the proper frequency. Several different methods are used to generate and demodulate SSB transmissions. A single sideband signal occupies about three KHz of spectrum. [Ref. 16:ch. 9, pp. 5-6]

(3) Frequency Modulation (FM). With FM, the carrier amplitude remains constant, while the carrier frequency is shifted proportionally with the intelligence to be conveyed. The intelligence amplitude is represented by the amount the carrier deviates from its center frequency. In other words, a 1000 Hz tone causes the carrier to shift back and forth in frequency 1000 times per second, while the volume of the tone is represented by how far the carrier swings from its center frequency (Figure 133). A narrow-band FM signal occupies a bandwidth of 20 KHz. [Ref. 16:ch. 18, pp. 1-2]

(4) Phase Modulation (PM). In PM, the phase shift of the signal is proportional to both the amplitude and frequency of the signal. This differs from FM where the

## Frequency Modulation

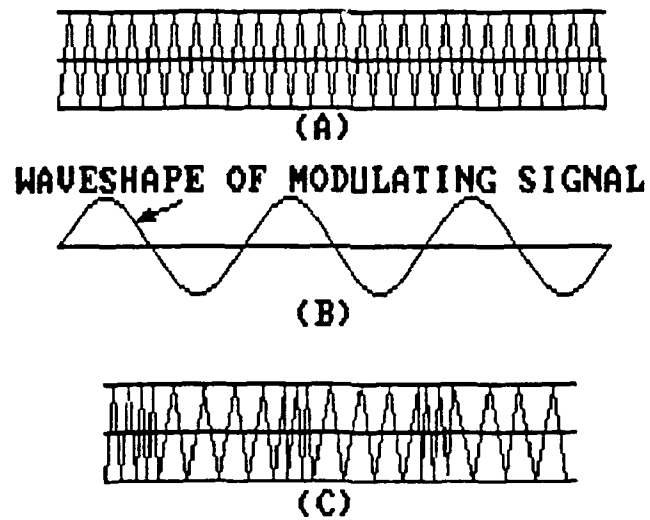


Figure 133. Frequency Modulation

frequency deviation is proportional to one, the amplitude of the modulating signal. [Ref. 16:ch 18, pp. 1-2]

(5) Audio Frequency Shift Keying (AFSK). AFSK can use any of the above modulation techniques to transmit digital information. A Modulator-Demodulator (MODEM) is used to convert digital signals to audio tones. These tones are usually several hundred Hz apart in frequency, with the "zero state" represented by one tone and the "one state" represented by another. These tones are superimposed on the carrier in the same manner as other analog signals. When these tones are received, they are sent to a MODEM where they are converted back to a binary output readable by digital circuitry. [Ref. 16:ch. 10, pp. 11-12]

(6) Frequency-Shift Keying (FSK). Digital signals can also be sent by shifting the carrier between two frequency states. One frequency represents a mark, or one, and the other frequency represents a space, or zero. In order to preserve bandwidth the frequency shift is usually one KHz or less. [Ref. 16:ch. 10, pp. 11-12]

(7) Phase-Shift Keying (PSK). PSK conveys digital information by shifting the phase of the carrier relative to a reference phase. As shown in Figure 134, one shift of phase represents a positive state, the other shift represents an inverted state. This is termed binary phase-shift keying (BPSK) [Ref. 16:ch. 19, pp. 31-32]. PSK is not limited to just two phase shifts. PSK systems which use four

## Phase - Shift Keying

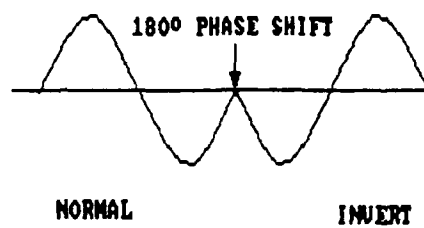


Figure 134. Phase-Shift Keying

or eight phase shift states are capable of conveying more information at any given carrier frequency, and are more spectrum efficient. PSK is used for conveying information and in generating direct sequence spread-spectrum transmissions [Ref. 16:ch. 21, p. 9].

#### b. Advantages and Disadvantages of Modulation Methods

As mentioned above, DSB-AM is the simplest modulation method. However, DSB-AM uses twice the bandwidth required to convey the intelligence, and the majority of the transmitter output power is used to broadcast the carrier. SSB and FSK solve these problems with much more complicated circuitry. However, both DSB-AM, SSB, and FSK suffer from fading, static, and background noise when the received signal is of moderate or less strength. The primary advantages of FM, PM, and PSK are the ability to produce a higher demodulated signal-to-noise ratio than other systems and their relative immunity from RF background noises which vary in amplitude, such as static. Their main disadvantage is that a much higher bandwidth is required to convey the intelligence. The limitation faced by all of these modulation schemes is only one signal at any time can occupy the same frequency without causing interference.

#### C. SPECIALIZED MODULATION TECHNIQUES

Several types of modulation have been developed to partially overcome the above limitations. Spread-spectrum or

code division multiple access (CDMA) disperses the transmitted signal over a wider frequency range than conventional modulation. This method of digital communications allows many users to simultaneously use the same frequencies. Amplitude-compandored single-sideband (ACSSB) allows the transmission of more analog voice signals in a given frequency spectrum than FM and is more immune to fading than SSB. Low data rate digital voice has the advantage of occupying a narrow bandwidth, requires less power than ACSSB, is more immune to radio frequency noise, and can be processed and filtered by digital circuitry. These advanced modulation techniques are required to support the numbers of users sharing the limited frequency ranges assigned to RDSS and MSS. CDMA, ACSSB and digital voice require much more complicated electronic circuitry than in conventional modulation systems.

1. Code Division Multiple Access

- a. Characteristics

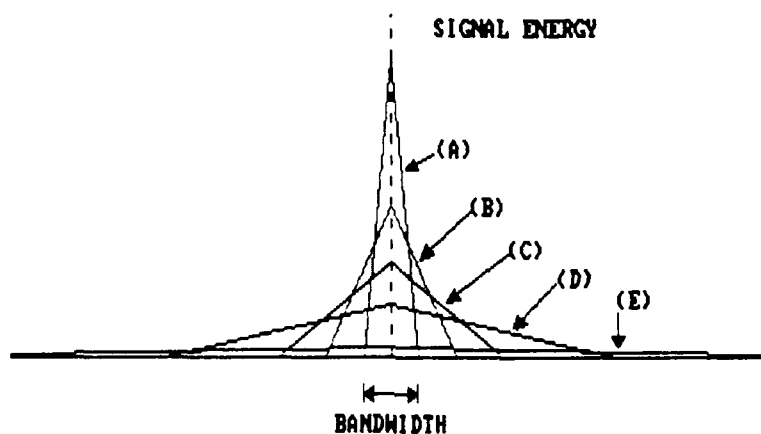
Geostar, OmniTRACS, Global Positioning System (GPS), and the Soviet Glonass system depend on spread-spectrum transmissions. The type of spread-spectrum signal used in these systems is termed code division multiple access (CDMA). Code division refers to the method of modulating each carrier frequency with a different binary spreading code. Multiple access implies that more than one transmitter-receiver pair is able to simultaneously use the frequency. CDMA has several

distinct advantages over the conventional narrow-band modulation techniques discussed above.

(1) No Requirement for Transmission Timing. A properly designed spread-spectrum system can allow random transmissions. This enables ground stations to transmit data randomly or on a scheduled basis with little chance of "colliding" with another signal and preventing communications. In the event that two stations transmit at exactly the same time and the message is not received, system logic can cause one or both stations to retransmit at a later time to be sure the message was received properly. [Ref. 16:ch. 21, pp. 7-8]

(2) No Frequency Separation is Required. As illustrated in Figure 135, spread-spectrum signals have a much greater bandwidth than conventional transmissions. The signals are spread by modulating them with special binary sequences. This dilutes the signal energy so that while occupying a very large bandwidth, the amount of power density present at any frequency within the spread signal is very low. The amount of signal dilution depends on transmitter power, distance from the transmitter, and the bandwidth of the spread signal. This spreading allows signals from many different transmitters to be simultaneously present over the assigned range of frequencies. The low power density enables the signals to be below the noise floor of a conventional narrow-band receiver, and thus invisible to it. This can permit spread-spectrum signals to share frequencies with conventional

## Spread Spectrum



A graphic representation of the distribution of power as the signal bandwidth increases. The unspread signal (A) contains most of its energy around a center frequency. As the bandwidth increases (B), the power about the center frequency falls. At C and D, more energy is being distributed in the spread signals's wider bandwidth. At E, the energy is diluted as the spreading achieves a very wide bandwidth. Bandwidth is roughly twice the bit speed of the PN code generator.  
[Ref. 16:ch 21, p. 9]

Figure 135. Spread Spectrum



transmissions without causing or experiencing interference.  
[Ref. 16:ch. 21, pp. 8-9]

(3) Ability to Reject Undesired Signals. The intended receiver uses the same copy of the transmitter's binary spreading sequence to despread the received signals and receive the transmitted data. Conventional transmissions and spread-spectrum signals which do not use the specific despreading code are suppressed in the signal processing. This enables spread-spectrum receivers to reject undesired spread-spectrum signals and conventional signals which are much stronger than the spread-spectrum power density. [Ref. 16:ch 21, pp. 8-9]

(4) Number of Users. Since CDMA is purposely designed to operate with interference from other signals, the total communications capacity can be quite large. CDMA system performance is statistically governed by the number and signal strength of users simultaneously transmitting over the same bandwidth. CDMA system design and service quality is based on the expected average amount of use. Greater than expected use causes a reduction in the digital signal to background noise ratio. This produces an increase in the reception (bit) error rate experienced by all users and a gradual decline in service quality as the number of users increases. This contrasts with other types of modulations (such as FM, ACSSB etc.) and multiple access formats (FDMA and TDMA) where performance is governed by the amount of interference experienced on the same

frequency or time interval. These systems degrade quickly and must be designed with a worst case scenario in mind. With properly chosen parameters, CDMA characteristics can allow many transmitters, ranging from thousands to millions, to efficiently share an allocated frequency spectrum. [Ref. 8:pp. 121-123]

(5) Range Determination. The structure of spread-spectrum signals also permits highly accurate timing and ranging measurements. Geostar and GPS use their binary signal-spreading sequence for range timing and position determination. [Ref. 8:p. 36]

b. Pseudorandom Noise Code

The binary sequence used to spread out the transmitted signal and despread the received signal is called a pseudo-random noise (PRN) code. The PRN code is created in a spreading-sequence generator. These are digital circuits located in the transmitter and receiver which are designed to produce a high-speed binary code output. This binary sequence is carefully designed to appear to be random and have approximately an equal mix of "zero" and "one" bits. A PRN bit is called a chip. PRN chip sequences are generated at a much higher rate, typically 100 or more times faster than the data bits which are being transmitted. [Ref. 8:pp. 36-38]

PRN codes are carefully chosen for certain properties which determine how well the spread-spectrum system will perform. One of the important considerations in

determining and designing a spreading-sequence generator is the amount of statistical similarity a PRN sequence has with conventional signals and with sequences used by other spread-spectrum systems. The greater the degree of similarity, the less the spread-spectrum receiver will be able to reject interference. This is because a statistical process known as correlation is physically realized in the receiver electronics to identify and detect signals with the desired PRN code. Signals spread with other PRN codes, time-shifted signals using the same PRN code, or signals which are not spread will differ statistically from the desired signal and produce a lower output from the correlator circuitry. A signal using the correct PRN code will produce a larger output from the correlator and will accurately convey the transmitted data. [Ref. 16:ch. 21, pp. 9-10]

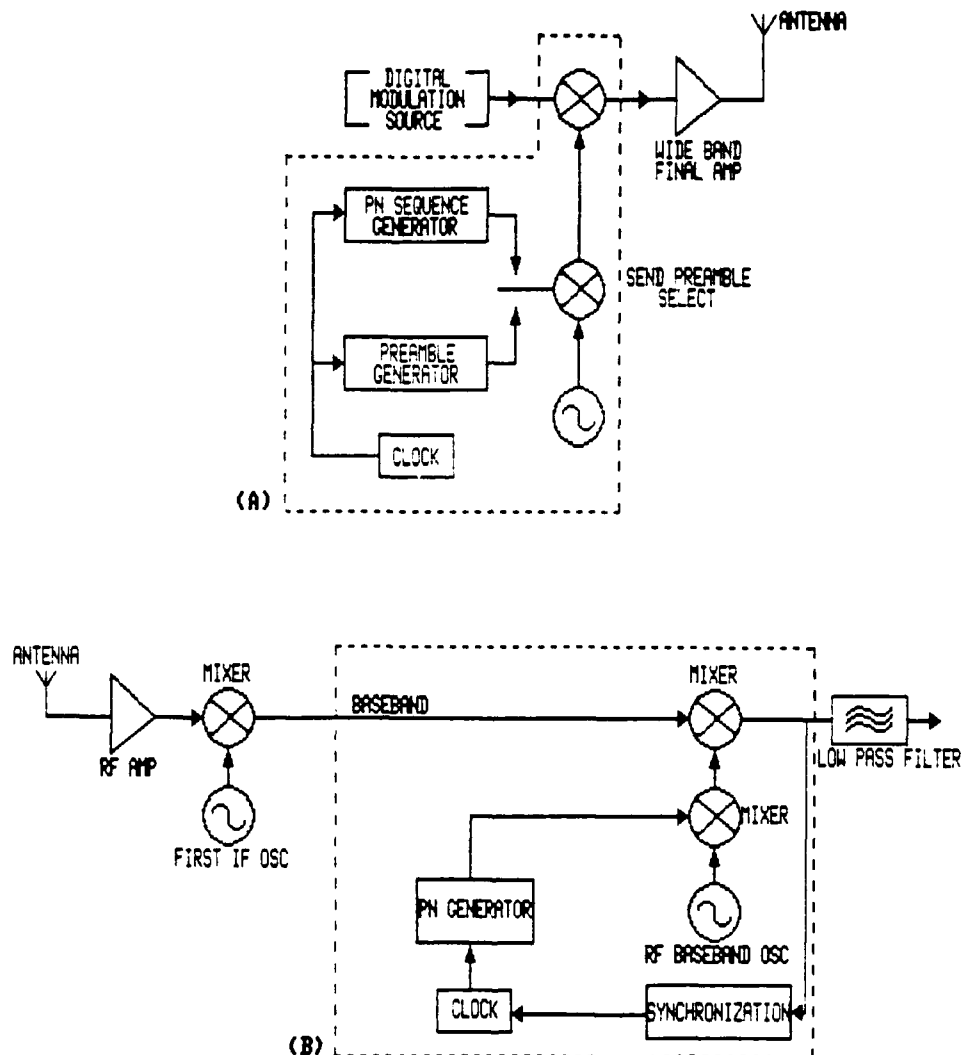
Many different types of PRN codes can be used in spread-spectrum systems. PRN code selection and generation is beyond the scope of this presentation.

#### c. Generic Theory of Operation

A simplified block diagram of a direct sequence spread-spectrum transmitter and receiver is shown in Figure 136. Block diagrams and circuitry for actual systems are far more complicated than shown in this conceptual illustration.

(1) Transmitter Operation. Synchronization is the most important item in spread-spectrum system. Unless both the transmitter and receiver are synchronized, the PRN

## Direct Sequence Spread Spectrum Transmitter and Receiver



The block diagram of a direct sequence transmitter is shown at A. The digital modulation source is mixed with a combination of the PN sequence mixed with the carrier oscillator. The PN sequence is clocked at a much faster rate than the digital modulation; a very fast composite signal emerges as a result of the mixing. The preamble is selected at the start of the transmission. Part B shows a direct sequence receiver. The wideband signal is translated down to a baseband (common) frequency. The signal is then routed to a correlator, mixing a baseband oscillator with the PN source and then mixing the result against the incoming baseband RF. The synchronization process keeps the PN sequence in step by varying the clock for optimal lock. After mixing, the information is contained as a digital output signal and all interference is spread to noise. The low-pass filter removes some of this noise. Notice that the transmitter and receiver employ very similar designs, one to perform spreading, the other to despread. [Ref. 16:ch 21, p. 10]

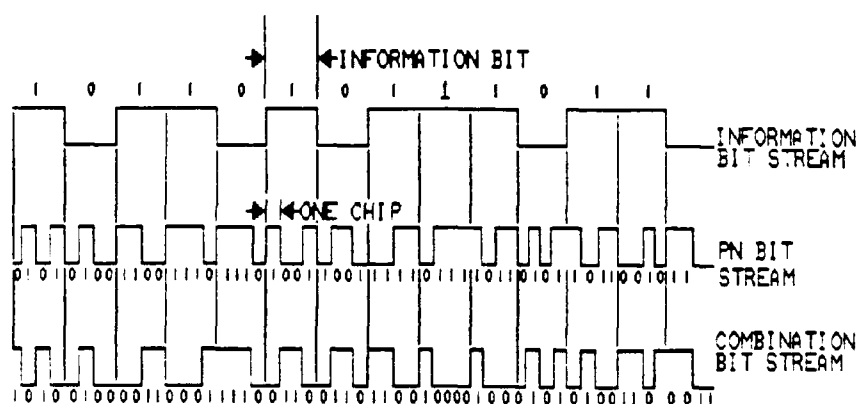
Figure 136. Direct Sequence Spread-Spectrum  
Transmitter and Receiver

codes will not correlate and demodulation of the signal can not take place. Synchronization is accomplished through a preamble signal that is sent by the spread-spectrum transmitter immediately before the transmitter enters the spread-spectrum mode. The preamble signal contains special binary sequences which enable the receiver to acquire and lock on the spread-spectrum signal.

The preamble performs three functions. First, the radio frequency carrier must be acquired by the receiver. Second, the receiver's local clock synchronization is established, and third, the spreading code must be synchronized. [Ref. 16:ch. 16, p. 12]

Once the preamble is sent, the transmitter enters the spread-spectrum mode. The pseudo-random noise generator is started and its output is mixed with the digital-modulation source. This mixing process is called bit inversion and is illustrated in Figure 137. An information bit of "one" causes all the PRN chips to be inverted, while an information bit of "zero" will leave the PRN code unchanged. The combined bit stream is routed to the balanced mixer circuit to modulate the carrier. The balanced mixer shifts the carrier phase between 0 and 180 degrees, depending if the PRN chip is a "zero" or "one." This is called Binary Phase Shift Keying (BPSK). A property of BPSK is that signal phase changes will also cause the signal's frequency to change. The more phase changes per unit of time, the more the signal will

## Bit-inversion Modulation



In bit-inversion modulation, a digital information stream is combined with a PN bit stream, which is clocked at many times the information rate. The combination is the exclusive-or sum of the two. Notice that an information bit of one inverts the PN bits in the combination, while an information bit of zero causes the PN bits to be transmitted without inversion. The combination bit stream has the speed characteristics of the original PN sequence, so it has a wider bandwidth than the information stream. [Ref. 16:ch. 21, p. 9]

Figure 137. Bit-inversion Modulation

spread in frequency. The resultant spread-spectrum waveform is then amplified to the desired power levels before being routed to the antenna. [Ref. 16:ch. 21, pp. 9-10]

In some systems a special sequence called epoch synchronization is used to maintain transmitter and receiver PRN-chip synchronization. Commonly, this is a short-bit sequence which is easily detected by a simple correlator called a digital matched filter. If the transmitter and receiver PRN code are out of synchronization, the epoch synchronization will bring the receiver's PRN code back in step with the transmitter's PRN sequence. [Ref. 16:ch. 21, p. 12]

(2) Receiver Operation. The received direct sequence spread-spectrum signal contains two types of modulation; one conveys information and the other contains the spreading sequence. To recover the information the spreading sequence must first be removed. This process is termed desreading.

After the spread-spectrum signal is received by the antenna it is routed through a broad-band radio frequency amplifier to boost the signal's power. The signal is mixed with the output of an oscillator and transformed to a lower baseband frequency. The signal is then routed into the correlator.

When the preamble is received, it starts the local receiver clock and synchronizes the receiver PRN

generator. A replica of the transmitter's PRN code is generated and routed to a second mixer where it is combined with an oscillator output that is the same as the receiver's baseband frequency. PRN synchronization is maintained by a delay-locked loop which corrects any timing offsets in the local code generator. This circuit is necessary because a one chip-synchronization error will prevent the receiver from recovering the message intelligence.

The received and locally-generated signals are combined in a third mixer. The bit-inversion modulation is detected at this point. When the intelligence was transmitted, a "one" data bit caused the PN code to be inverted, and a "zero" data bit left the PN code unchanged. When the received and locally-generated PRN sequences are combined, the received "zero" data bit contains uninverted PRN code chips that match up, or correlate, with the PRN code generated by the receiver. However, the received "one" bit will not correlate since its PRN code chips are inverted. Since these chips are "opposite" of each other, the correlator circuit will produce no output for a "one" data bit.

Unless the spread-spectrum transmission is very strong, it is likely that undesired signals or background noise received within the passband will be present and corrupt some of the desired signal. These interfering signals will not correlate with the locally-generated PRN code and will fall in and out of match on a random chip-by-chip basis.



However, since a data bit is typically composed of 100 or more chips, corrupting some of the chips in each bit will not destroy the intelligence. For example, in a 100-chip bit, a randomly distributed corruption of 25 chips still results in 75% of the chips being correctly received. If a perfect match of PRN codes in each data bit equals a value of one, then the correlation would be 0.75. So, for a "zero" data bit where the PRN codes were not inverted, the average output level over the time it took to transmit all 100 chips would be equal to 0.75. Conversely, for a "one" data bit where the PRN codes were inverted, the average output level would be 0.25. As illustrated in Figure 138, a perfect correlation results in two values, zero and one. With 75% correlation, the two values represented would be 0.25 and 0.75. Even though perfect correlation was not obtained, there is enough difference between these values to discern the difference in binary state and reconstruct the original transmission. This difference is reflected in changing voltage level output from an averaging circuit. This demodulated digital signal is then sent farther into the equipment where it is processed. [Ref. 16:ch. 21, pp. 10-12]

The averaging process over time is the key to interference rejection. Background noise and interfering signals do not destroy the intelligence, they just reduce the statistical correlation. Much lower correlations than in the

## Averaging Circuit Output Levels

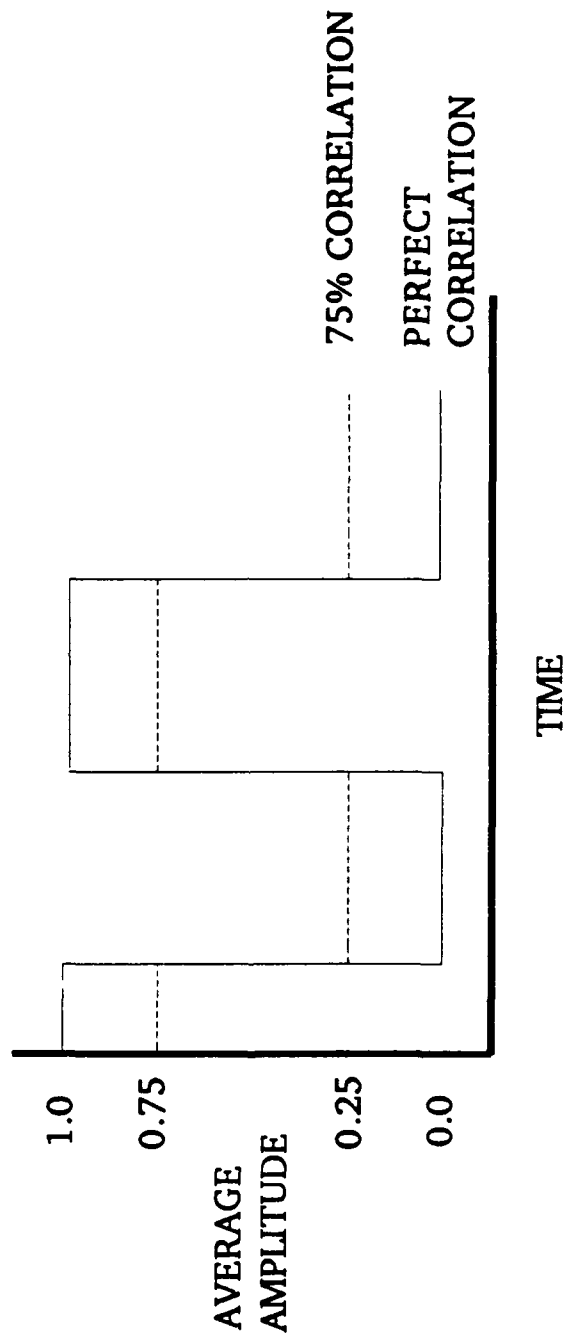


Figure 138. Averaging Circuit Output Levels

example can be used with properly chosen parameters and error-checking routines. This allows processing gain, or the ability to use lower transmitter power and receiver gain than would be required in conventional communication systems. Processing gain allows spread-spectrum satellite systems to use lower power transmitters on vehicles and in orbit. It is a factor which enables antennas to be smaller and have lower gain than would be required with other types of modulation. [Ref. 8:pp. 35-36]

d. Frequency Hopping and Hybrid Systems

PRN and other types of codes can be used in a different manner to control the specific frequency of a carrier, independent of the type of modulation used. The transmitter's frequency synthesizer output is controlled by the code sequence, and is termed frequency hopping. Unless the receiver uses a copy of the hopping code to control its frequency synthesizer, it will not be able to lock on and track the received signal [Ref. 16:ch. 21, pp. 8-9]. Frequency hopping is illustrated in Figure 139. Qualcomm uses a hybrid CDMA and frequency-hopping system to control the frequency distribution and power density of all transmitting OmniTRACS terminals [Ref. 94:p. 204].

e. Range Determination

Ranging provides a measurement of range (distance) between two points. Measurement of distance is accomplished by transmitting a signal from one point to the other and back,

## Frequency Hopping

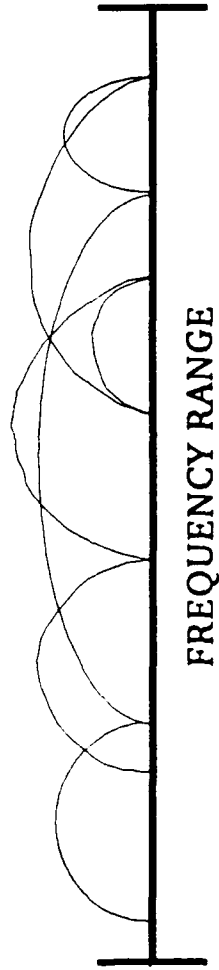


Figure 139. Frequency Hopping

and measuring the round trip transit time. Assuming no other propagation delays, range is equal to one-half the signal transit time multiplied by the speed of light (300,000 Km/sec or 186,000 Mi/sec). Accuracy of the range measurement is dependent upon clock timing accuracy. Radar is based on this principle.

PRN codes can also be used to measure range. The correlation between the transmitted and received signals is monitored, and the number of code chip shifts needed to align the two signals is counted. Since the chips have a known time duration, the total number of chips is equal to the time delay. The smaller the chip's time duration, the higher the range resolution. To obtain accuracies higher than one chip resolution, it is necessary to phase-lock onto the incoming signal and measure fractions of a chip shift. As in radar, assuming there are no other propagation delay, range is equal to one-half the time delay (number of chips multiplied by the chip duration) multiplied by the speed of light. [Ref. 8:p. 41-42]

## 2. Amplitude Compandored Single Sideband

### a. Pilot Tone

SSB uses about one-fifth the spectrum required by narrow-band FM. This is an obvious advantage when attempting to maximize the limited spectrum which has been assigned to mobile satellites. Using SSB at the higher frequencies presents problems because it is difficult to be sure the

original carrier at the transmitter and the carrier which is reinserted by the receiver are at precisely the same frequency. This error causes an unpleasant change in the pitch of the received audio, and can make the signal unintelligible. An operator can compensate for the error by adjusting a receiver-tuning circuit to bring the carrier frequencies into alignment. In mobile operations this has proven to be an aggravation and is difficult for untrained operators.

ACSSB avoids this problem by transmitting one sideband and a special pilot tone as shown in Figure 140. The pilot tone is sufficiently separated in frequency from the sideband that the two signals do not interfere with each other. The tone is transmitted at a power level below the maximum sideband amplitude. The transmitter operates at about 10% power when there is no analog signal.

In the receiver, the pilot tone is compared with a reference oscillator in a phase-lock-loop (PLL) circuit. The difference voltage produced by the PLL is used to shift the receiver tuning until the frequency error is eliminated.

The pilot tone serves other functions as well. It is used to control squelch and automatic gain control (AGC) circuits, and can be modulated to convey data. [Ref. 16:ch. 18, p. 17]

## Amplitude Compandored Single Sideband

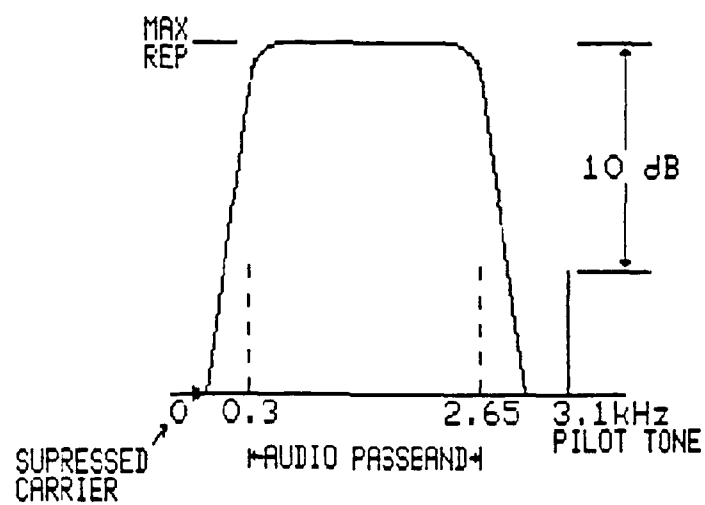


Figure 140. Amplitude Compandored Single Sideband

b. Compandor

The term "compandor" is short for "compressor" and "expander." In ACSSB, the analog voice is compressed for transmission and expanded in the receiver. Compandoring allows a higher signal-to-noise ratio and voice quality at a much lower transmitter power than with SSB. This is important because of the limited antenna gain and transmitter power available in mobile and satellite systems.

(1) Compression. It is difficult to maintain a constant voice intensity when speaking into a microphone. This can cause large fluctuations in the transmitter's peak-to-average-power ratio and make reception more difficult. As illustrated in Figure 141, compression reduces the peak-to-average ratio, and raises the average power level of a SSB signal. Compression can be accomplished in several ways, but unfortunately all have a shortcoming. By compressing the amplitude peaks, the background noise picked up by the microphone increases compared to the peak audio signal. The transmitted waveform also picks up noises from the radio channel and the added compression circuitry. These higher intensity background noises can make listening more difficult. This is particularly true in transmissions from vehicles where there is a lot of ambient background noise.

(2) Expansion. Passing the received signal through an expander reverses most of the bad effects of compression. This improves the signal-to-noise ratio and



## Compondoring

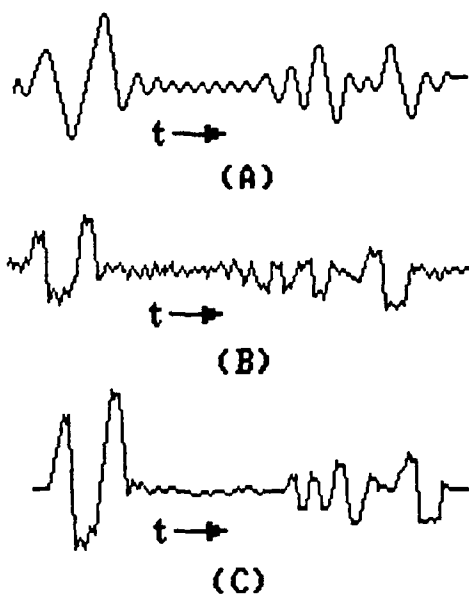


Figure 141. Compondoring

makes listening easier by providing a cleaner signal over a wider dynamic range. The expander will continue to operate with weak ACSSB signals as long as they are above the background radio-noise level. This reduces the effect of signal fading. However, when the ACSSB signal falls into the background radio noise the expander will lose its reference signal and will not work properly. [Ref. 16:ch. 7, pp. 7-8]

### 3. Digital Voice

As its name implies, digital-voice modulation converts an analog-voice signal into a digital-data stream. The data are decoded by the receiver and converted back to an analog voice signal. Digital voice has several advantages over ACSSB. Digital speech is easily encrypted for security. Unlike ACSSB, where transmitter output power fluctuates with modulation amplitude, digital voice has a constant modulation envelope and power requirement. This makes the design of mobile and satellite RF power amplifiers less demanding. Digital signals, when used with error correction, allow lower power levels than ACSSB. In an all-digital network, the same modems can be used for speech, data, and system control. Future generations of satellites will require signals to be digital to allow onboard signal processing and routing. Digital-voice modulation can be divided into two broad categories.

#### a. Waveform Coding

This method represents an analog signal with a digital data stream which, when decoded, produces a replica as close as possible to the analog signal. This technique is illustrated in Figure 142, and is used in compact disk players and telephone systems to produce high quality music and natural sounding speech. The main disadvantage of waveform coding is the requirement for high data rates, which for voice communications range from 16 kilobits per second (kbps) to 64 kbps. Using the general rule that one bps requires one Hz of bandwidth, waveform coding uses between 16 and 64 KHz of RF spectrum. This far exceeds the maximum ACSSB bandwidth of five KHz, and drastically reduces the numbers of channels available in a satellite communication system. Attempting to conserve bandwidth by reducing the waveform coding to below 16 kbps results in unacceptable voice quality. This is because there is not enough data to accurately represent the analog wave form, and the large errors distort the decoded analog signal. [Ref. 16:Ch. 8, pp. 21-22]

#### b. Source Coding

To operate below 16 kbps requires mathematically modeling human voice-production. The goal with source coding is to reproduce the sound, not the waveform. Most source code systems model speech as the output of a vocal tract, with the goal of preserving the significant properties of the waveform

## Waveform Coding

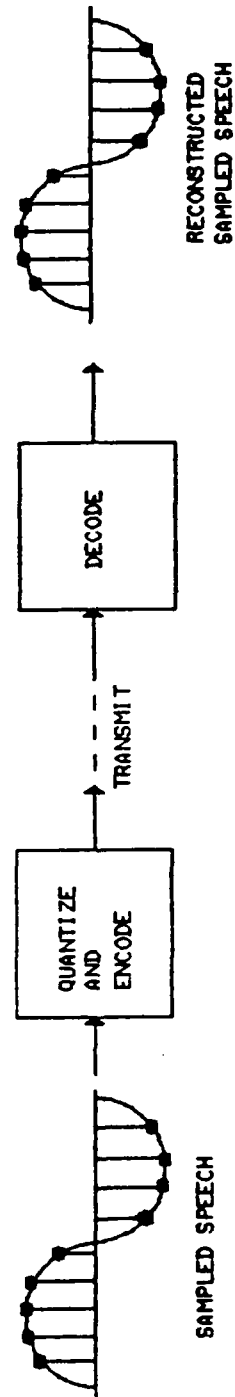


Figure 142. Waveform Coding

for synthesizing a signal at the receiver which sounds very much like the original. [Ref. 98]

The core of most voice coders (vocoders) is the analysis-synthesis model. Figure 143 is an example of one type of vocoder. The speech is sampled over very brief intervals and routed to a speech analyzer. Parameters such as pitch, volume, short-term and random waveform variations are quantized and encoded. In the receiver, these parameters are inserted into the model to produce the synthetic speech. [Ref. 99:insert E]

Early low data-rate vocoders sounded mechanical. The challenge for mobile-satellite voice communications is to develop 4800 bps systems which sound similar to a long-distance telephone call, provide good performance with mobile background noise, are signal-fade resistant, are inexpensive and available in a small electronics package. Several promising 4.8 kpbs source coding models which meet these criteria are being evaluated under the NASA Mobile Satellite Experiment (MSAT-X) program for use in the mobile satellite systems. [Ref. 100]

#### D. ADVANTAGES OF DIGITAL COMMUNICATION

Digital communication systems use binary numbers to convey information. The ability to process and store digital information has many advantages over conventional analog communication systems. Some of these are discussed below.

# Source Coding

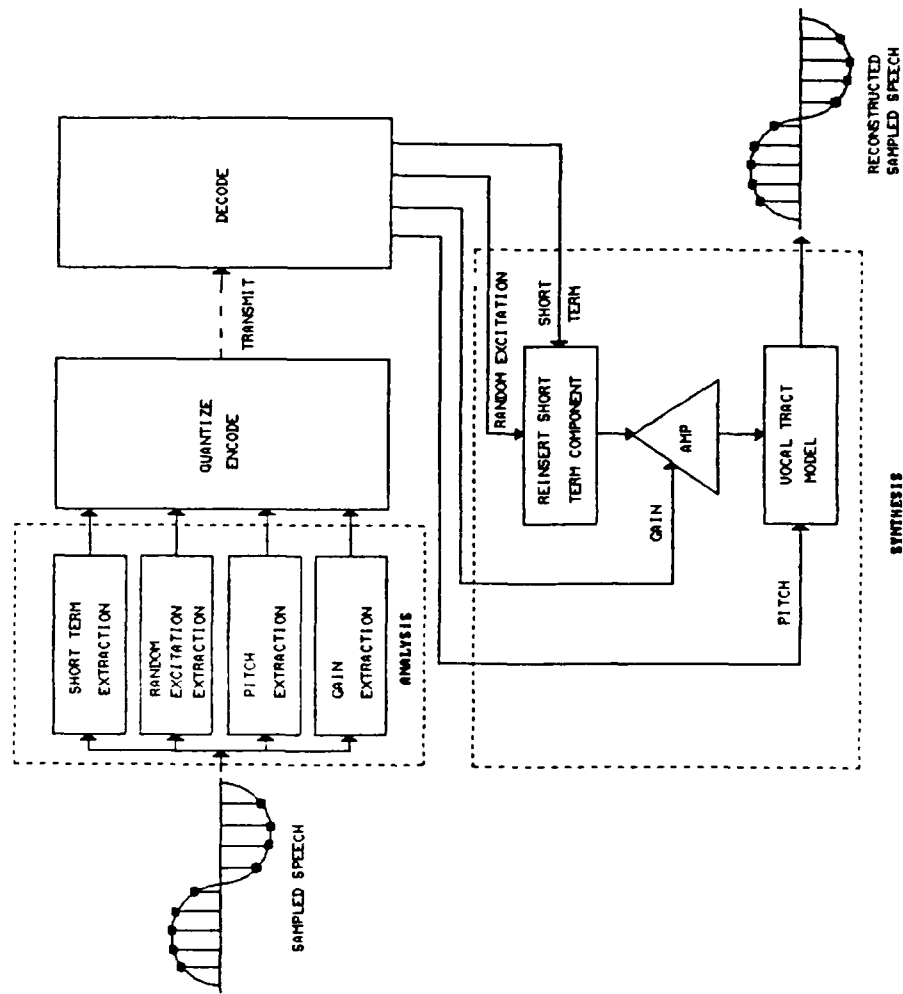


Figure 143. Source Coding

## 1. Error Detection and Correction

There is no such thing as an error-free communications channel, although many approach the level of perfection. In conventional systems, an erroneous-information segment is a piece of information lost. Lost information can be reduced or completely eliminated by using digital processing and communication protocols.

Most background noise is analog and randomly distributed. Special digital filters and processing circuits are able to remove random noise as long as it does not exceed certain values. Breaking digital data and text streams up into blocks allows the use of error detection. The data are processed prior to transmission and a unique error-checking code is added. After the receiver demodulates the signal the data are again processed. The transmitted code is checked against the code calculated by the receiver. If the two codes do not agree, the receiver assumes the data block is incorrect and a retransmission is requested. Two types of error-checking codes are the cyclic-redundancy check (CRC) and the frame-check sequence (FCS). [Ref. 101]

Forward-error correction (FEC) allows the receiver to reconstruct missing or incorrectly received data and text as long as certain levels are not exceeded. The data stream is routed through a FEC encoder prior to transmission. Additional code symbols may be added, and the data structure is changed. Upon reception, the FEC data are processed

through a decoder and reconstructed. Error-checking codes can also be incorporated to request retransmission in the event that FEC was not successful. Viterbi encoders are widely used in satellite and data communications systems. FEC is quite complicated and a further discussion is beyond the scope of this thesis. [Ref. 16:ch. 21, p. 6]

## 2. Packet Communications

Unlike analog modulation which requires a dedicated and continuous communications circuit between the transmitter and receiver, a digital data and text stream can be subdivided and transmitted in segments called packets. At a minimum, each packet will contain the identification of the sender and receiver, the packet-sequence number, the information to be conveyed, and control and error-checking information. Some packet systems also incorporate FEC. These packets are individually transmitted and routed according to their destination address by packet-network controllers. Equipment along the communication path and at the destination uses the error-checking code to determine if the packet was correctly received. Correctly received packets are acknowledged, while an incorrectly received packet generates a request for retransmission. This ensures that data are received without error. The data are extracted at the destination from each packet and put back together to reform the original transmission.



The X.25 packet-communication protocol is used by many nationwide-packet networks and much of the communication industry. This standardized interface enables many different types of data and computing equipment to efficiently and inexpensively share common packet-communication systems. [Ref. 101]

### 3. Data Management and Communication Efficiencies

From a communications-throughput standpoint, text and data communications are more efficient in certain applications than analog or digital voice. This is because text and data can be electronically conveyed at a far higher rate than a person is capable of speaking. This reduces costs because less transmission time is required and more users can be accommodated by the communication system.

Sender entry of keyboard text and data also permits direct input to computerized systems and eliminates receiver transcription errors. The ability of computerized equipment to store, retrieve, manipulate, and display messages and data can be much more efficient than manual, hand-transcription systems.

## E. SATELLITE COMMUNICATIONS

### 1. Satellite Orbits

#### a. Geostationary

A satellite launched into orbit with an inclination to the equator of zero degrees will always remain above

the equator. If this satellite has a circular orbit and travels from West to East, at a height of about 35,800 kilometers (22,250 miles) above the Earth, the satellite's angular velocity will equal the rotation of the Earth about its axis. Thus, this satellite will have an orbit with a period of 24 hours and, to an observer on the ground, appear to be hanging motionless in the sky. [Ref. 102:ch. 8, p. 15]

The geostationary orbit is ideal for a communications satellite. Ground-station antennas can remain pointed in the direction of the satellite without complicated tracking mechanisms. Since the relative position of the satellite does not change, doppler shifts (changes of frequency due to relative motion) do not occur. As illustrated in Figures 144 and 145, at geostationary altitude the satellite has almost complete coverage of one-third of the Earth.<sup>3</sup> This allows the use of fewer communication satellites than would be required with other types of orbits.

The major disadvantage of geostationary orbits occurs at high latitudes, where the elevation angle of the satellites are low to the horizon and the signals can be blocked by buildings, foliage, and hilly terrain. Latitudes in Northern and Southern hemispheres greater than approximately 80 degrees are not covered at all. Also, the signal spreading loss over the 35,800 kilometer path requires higher

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<sup>3</sup>Generated using "GrafTrac II" software.

# EARTH COVERAGE FROM GEOSTATIONARY ORBIT

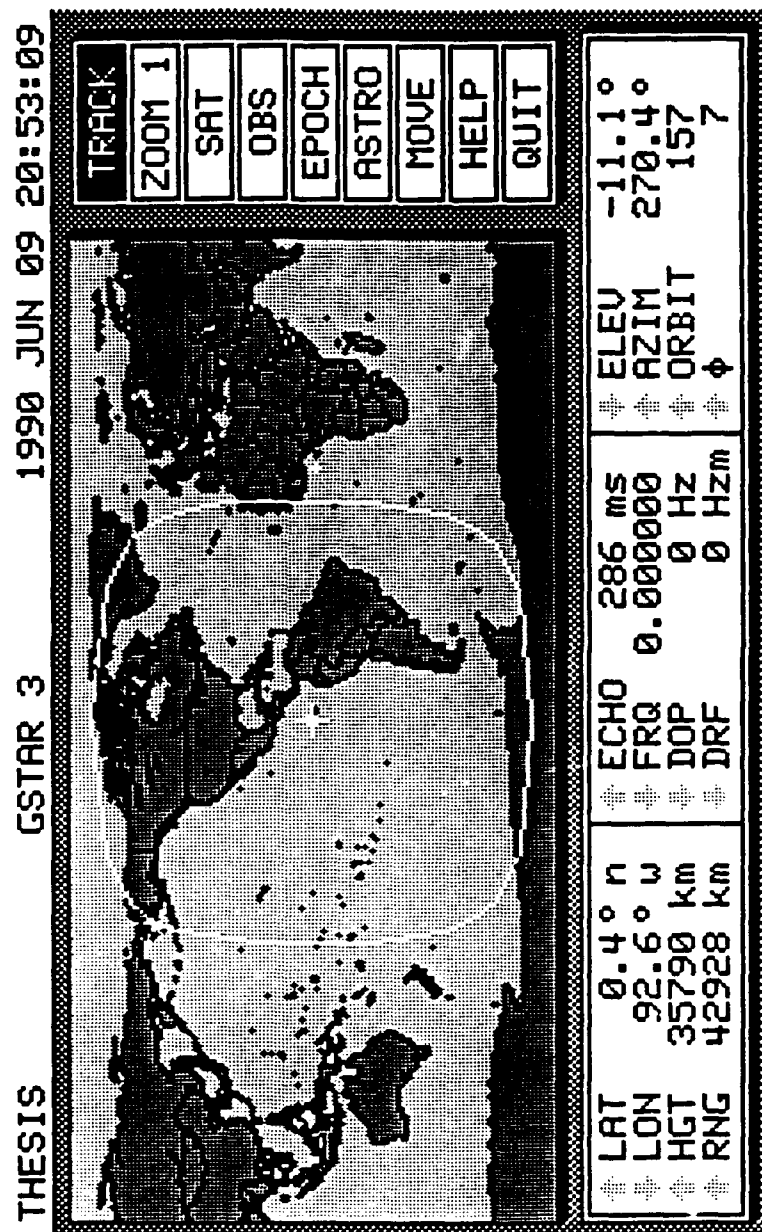


Figure 144. Earth Coverage from Geostationary Orbit

## VIEW FROM GEOSTATIONARY ORBIT

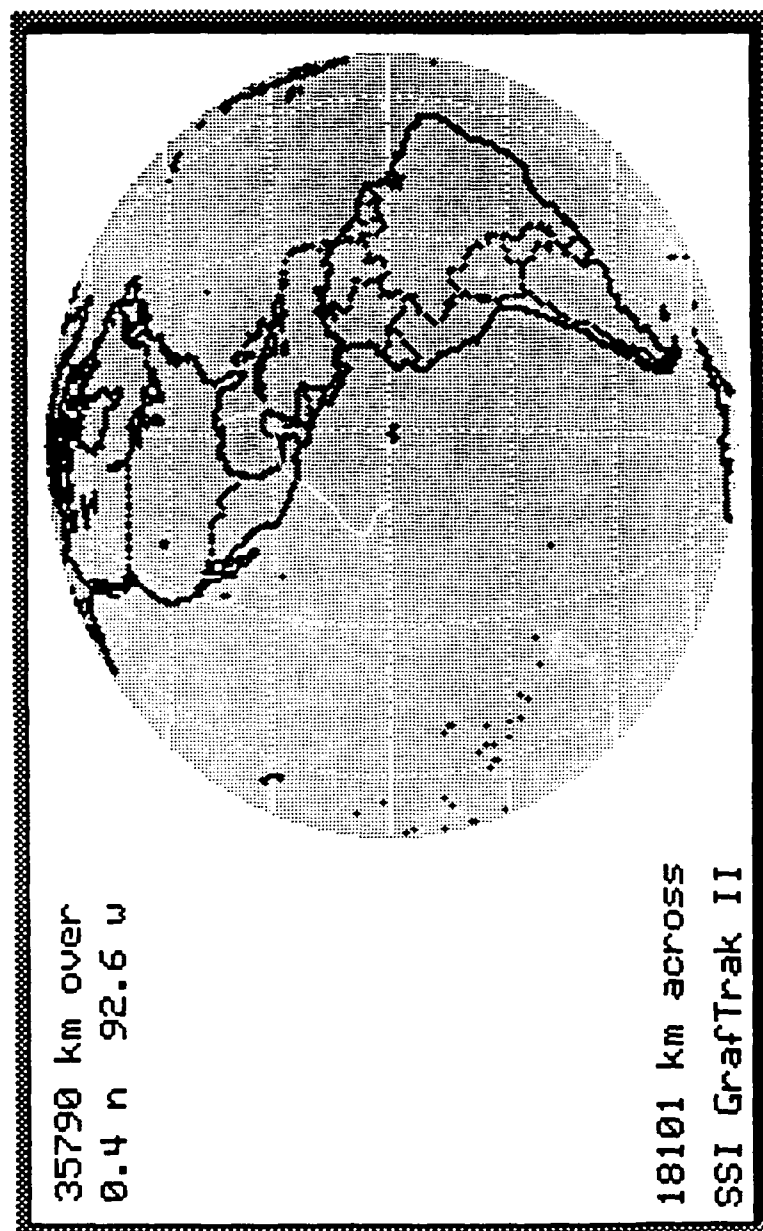


Figure 145. View from Geostationary Orbit

transmit power, more sensitive receivers, and higher gain antenna systems than do lower orbiting satellites.

b. Non-geostationary Orbits

A satellite in any orbit which is not geostationary will always move relative to an earth station. As shown in Figures 146 and 147, a satellite in a low altitude orbit has visibility of a much smaller portion of the Earth. However, a low altitude satellite placed in a polar orbit can cover the entire Earth one or more times a day. Complete and continuous worldwide coverage can be obtained by placing a constellation of satellites in several orbital planes which are inclined to the equator.

To place a satellite into low orbit requires less energy than to boost a satellite to geostationary altitude. Besides polar coverage, low altitude orbits offer the advantages of reduced transmitter power, receiver sensitivity, and lower gain antennas. The doppler shift exhibited by low orbiting satellites can be used to determine location on the earth and satellite orbital data.

To overcome the problems of low geostationary satellite elevation angles at high latitudes, the Molniya orbit can also be used. As illustrated in Figure 148, this type of orbit is elliptical, inclined to the equator at approximately 63 degrees, and has a period of eight to 12 hours. The perigee (lowest point of the orbit) is in the Southern hemisphere. Apogee (highest point), where the

# EARTH COVERAGE FROM LOW ALTITUDE ORBIT

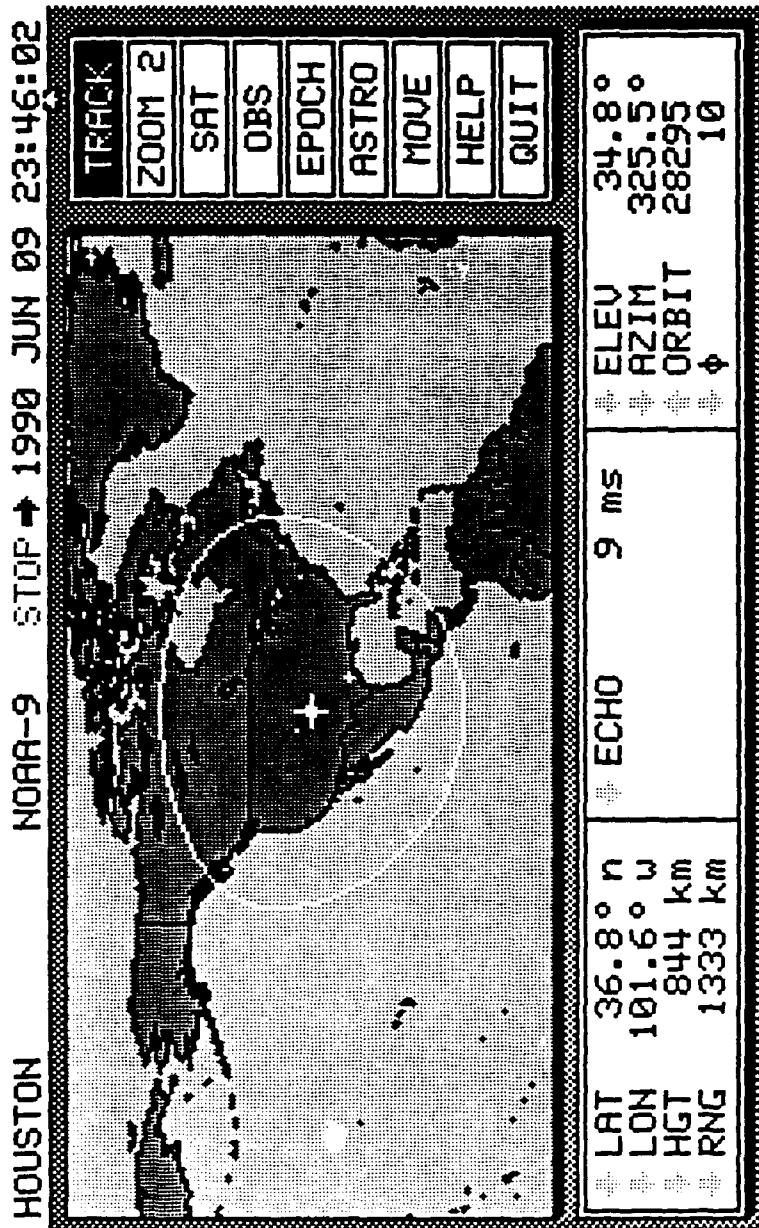


Figure 146. Earth Coverage from Low Altitude Orbit

## VIEW FROM LOW ALTITUDE ORBIT

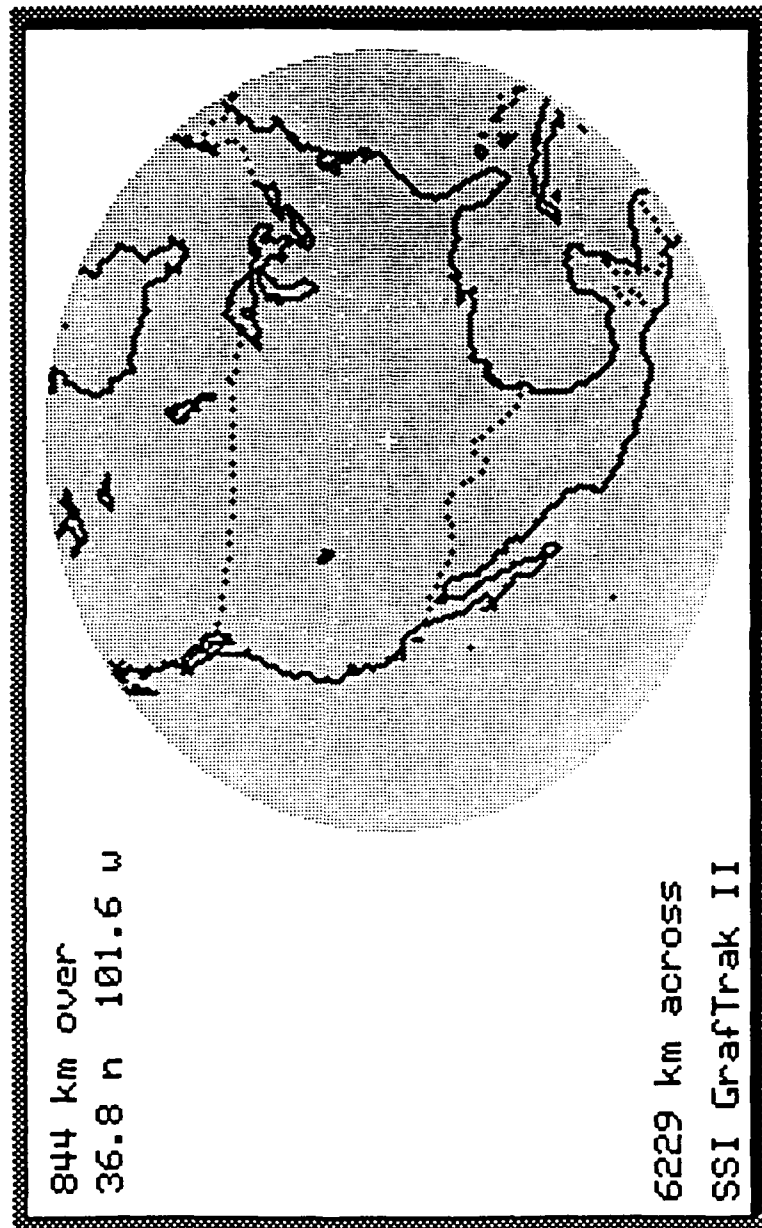


Figure 147. View from Low Altitude Orbit

## Molniya Orbit

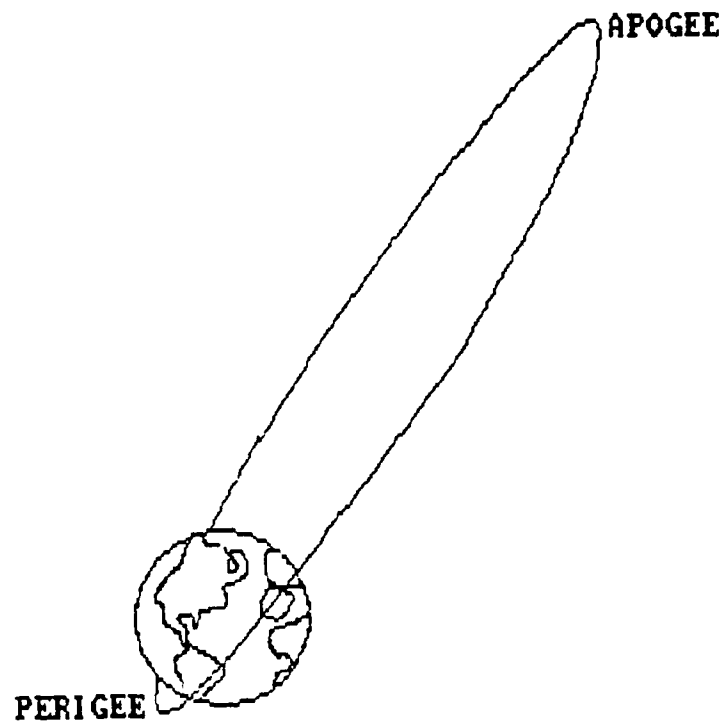


Figure 148. Molniya Orbit



satellite moves slowly, always occurs over 63 degrees North latitude. At apogee, nearly one-half of the Earth, most in the Northern hemisphere, is in view. A series of three satellites in 12 hour Molniya orbits provides continuous coverage of most of the Northern hemisphere. [Ref. 103:ch. 8, pp. 16-17] Coverage of the Soviet Molniya 1-74 satellite at apogee is shown in Figure 149. This type of orbit has been suggested for MSS use in high latitudes where terrain and buildings could easily block out low-elevation geosynchronous MSS satellites.

## 2. Communication Satellite Configuration

A communications satellite usually acts as a "bent pipe" or a repeater, transforming the received signals to a different frequency for retransmission back to earth. This general arrangement is illustrated in Figure 150. Separate stations on the ground each transmit their individual signals to the satellite, which in turn simultaneously relay these signals to other ground stations. [Ref. 103:p. 21]

Communications satellites are designed to use different uplink and downlink frequencies. Uplink is the term for the segment of the communications path between the earth and the satellite. Conversely, downlink is the term for the portion of the communications between the satellite and the ground. The uplink and downlink paths are on different frequencies to permit simultaneous satellite relay of signals without interference.

## VIEW FROM MOLNIYA ORBIT AT APOGEE

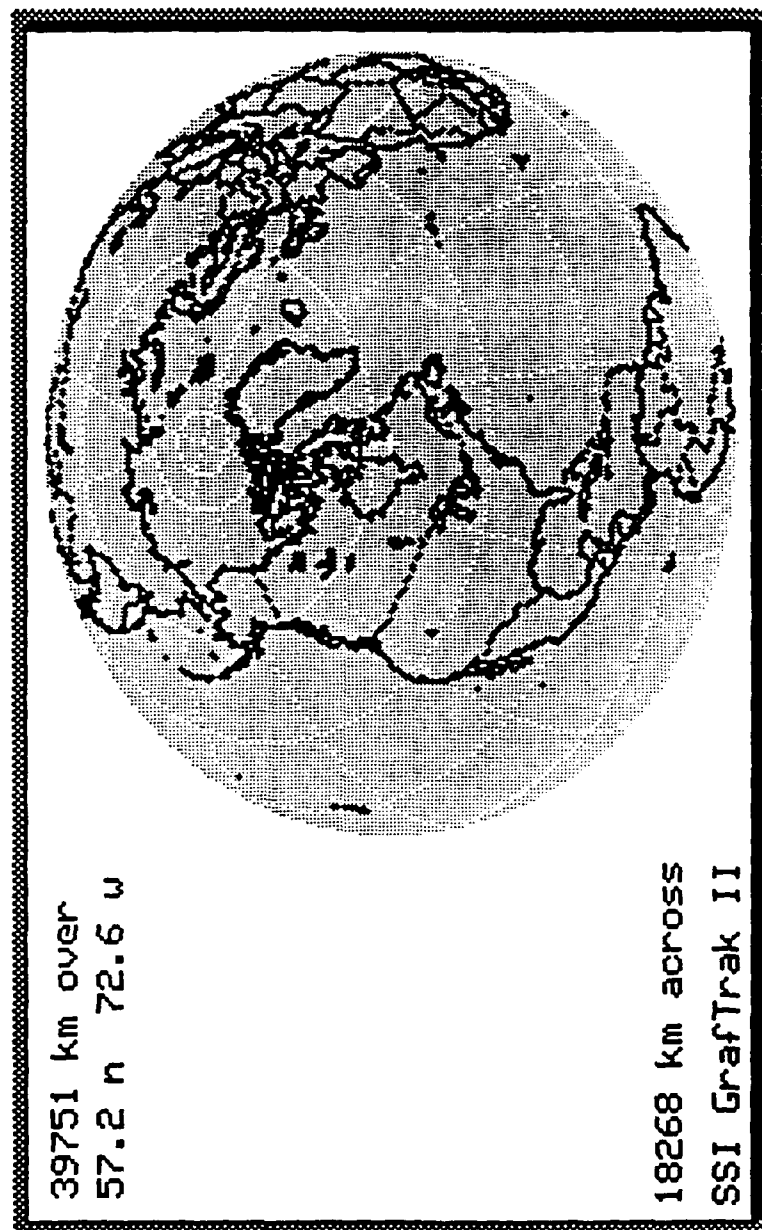


Figure 149. View from Molniya Orbit at Apogee

## "Bent Pipe" Communication Satellite

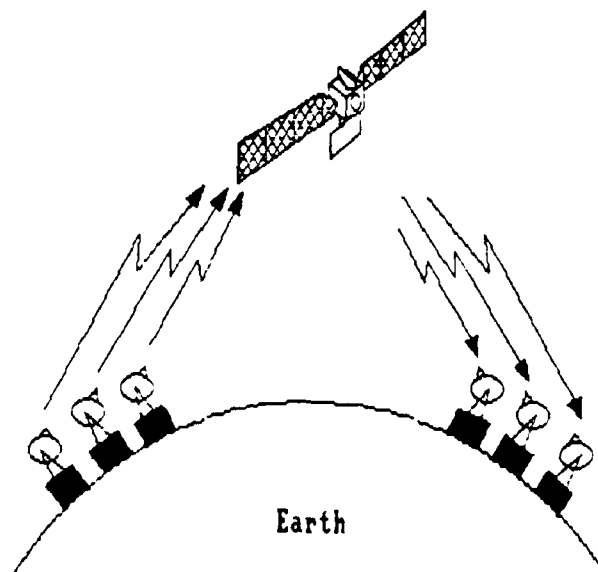


Figure 150. "Bent-Pipe" Communication Satellite

Communication satellite transponders can relay many independent signals through frequency translation and amplification. Received uplink signals within the passband are routed through a low-noise preamplifier and are down converted to an intermediate frequency. The signals are filtered to limit the bandwidth of the relayed spectrum and amplified. Mixers then up convert the signals to the transmit frequency. The RF is then sent through power amplifiers and to the downlink antennas. [Ref. 67:p. 41]

Very substantial costs are involved in the construction, launch, and operation of a communications satellite. In order for satellite communication to be cost effective, the system must be able to handle enough traffic to generate sufficient revenue to cover capital costs, operating expenses, and provide a profit. This requires that systems be designed to maximize the number of users to keep individual costs affordable. Frequency spectrum, orbital positions, satellite antenna size and transponder power are limited, and they must be used as efficiently as possible.

a. Frequency Reuse

Figure 151 illustrates the use of dual polarization and spot beams to reuse the assigned spectrum. [Ref. 103:p. 127]

(1) Dual Polarization. Radio waves are composed of electrical and magnetic fields. Polarization refers to the orientation of these fields. When radio waves are

# Frequency Reuse Methods

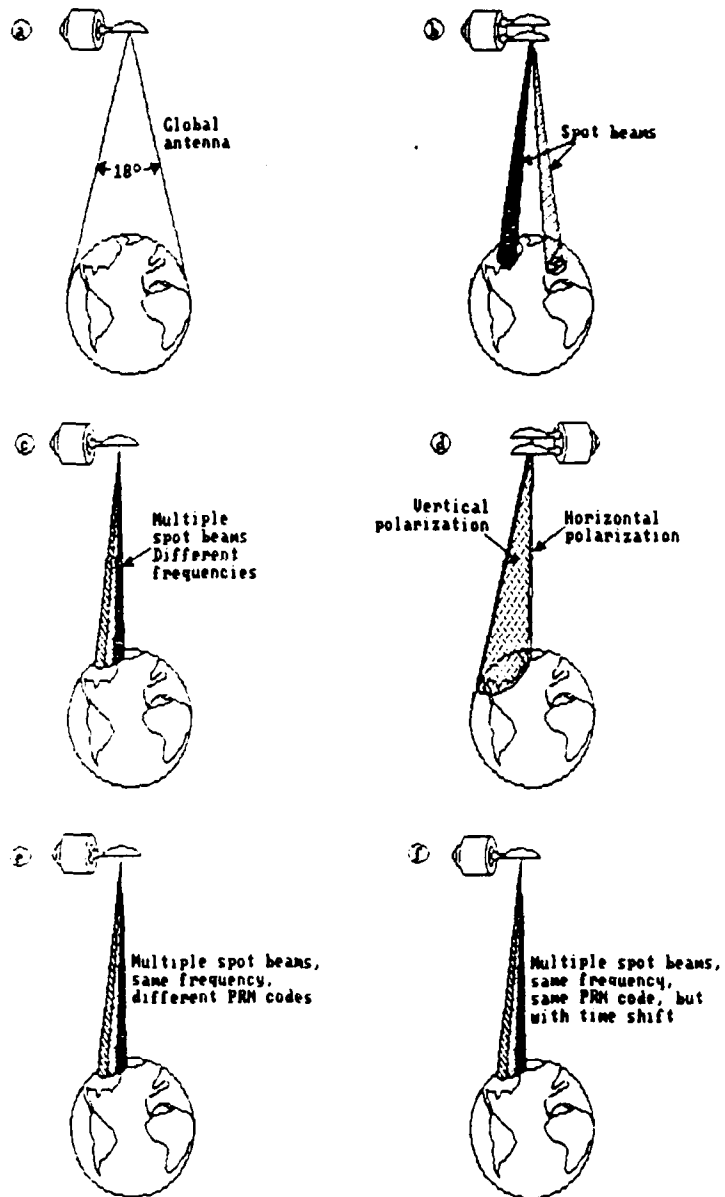


Figure 151. Frequency Reuse Methods

transmitted, they are polarized in a certain direction (e.g., horizontal and vertical). A receiving antenna which is oriented in the same polarization will receive a stronger signal than if it was oriented to the opposite polarization. With dual polarization, the same band of frequencies can be reused by transmitting two oppositely polarized beams. As long as the polarizations are maintained between points, and the antenna systems aligned with each polarization, the transmissions can be separated with no interference. Depolarization occurs when the atmosphere and water droplets cause a change in polarization. This can couple one channel into the other and produce interference. Atmospheric depolarization is negligible below 10 GHz, but can make use of polarization difficult between 10-30 GHz. [Ref. 103:pp. 122-126]

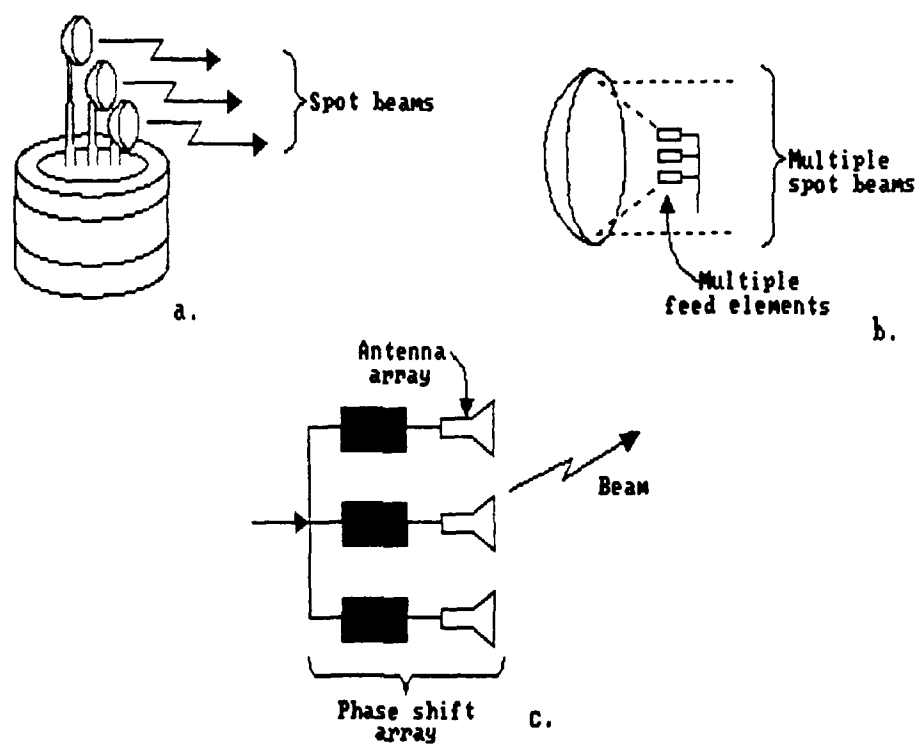
(2) Spot Beams. A global beam will send the same carrier and information to all points which are visible to the satellite. Spot beams can be used to send different information to different points while using the same carrier frequency. Spot beams also have the advantage of condensing energy which would have been distributed over the visible surface of the Earth into a smaller area. This effectively increases the received signal strength at both the earth station and the satellite receiver.

The main problem with multiple spot-beam frequency re-use is avoiding interference between adjacent

beams. This requires careful shaping of each spot-beam pattern to reduce beam spillover. Several methods are available to reduce interference. Different frequency bands can be used for adjacent beams. Frequency reuse is still accomplished since every third beam can have the same carrier frequency. Beam separation can also be accomplished by polarization. Different PRN codes can be used in adjacent spot beams to increase the capacity of spread-spectrum systems. Finally, spot beams can hop in a time sequence over the Earth's surface, staying on a location just long enough for burst transmissions to be sent and received. [Ref. 103:pp. 126-130]

Multiple beams can be produced in one of the three ways illustrated in Figure 152. The simplest uses separate antennas for each beam. Multiple beams can also be generated from a reflector fed by multiple feed elements. The feed elements reflect off a common parabolic dish, with each feed being focused in a separate direction. Each beam will have the same polarization as its feed. A third method is using a phased-array antenna. The direction and shape of a beam can be controlled by shifting the phase of the modulated carrier that is transmitted through multiple antenna elements. A different frequency band can be formed by separately phasing a different carrier frequency into another spot. Only a single antenna array is used, but the phase-shifting mechanism

## Multiple Beam Generation



Multiple beam antennas. (a) Separate antennas. (b) Multiple feed, single reflector. (c) Array

Figure 152. Multiple Beam Generation



becomes complicated. The smaller the spot beam to be formed, the larger the antenna array.

A disadvantage of multiple beam antennas is the increase in complexity and weight of the satellite. Beam pointing also becomes more critical than with a global coverage antenna. A two-degree shift in pointing accuracy will move the spot beam pattern approximately 800 miles. The additional hardware and structure needed for spot beams can greatly add to the cost of the satellite. [Ref. 103:pp. 128-130]

#### b. Multiple Access

Communication satellites are designed to handle multiple simultaneous uplinks and downlinks. Since all uplink carriers must pass through the common satellite to complete their downlink transmissions, the general system operation is called multiple-access communications. All receivers observe the same satellite transmissions, and therefore the multiple-access system must allow separation of the downlink segments. Separation is achieved by requiring all uplink transmissions to conform to a specific format. Three basic forms of multiple-access formats are shown in Figure 153. Each of these can be used separately or in combination, and are not just limited to satellite systems. [Ref. 103:pp. 20-23]

##### (1) Frequency Division Multiple Access (FDMA).

FDMA is the simplest multiple-access format. Earth stations are assigned specific uplink and downlink frequencies within

## Basic Multiple Access Techniques

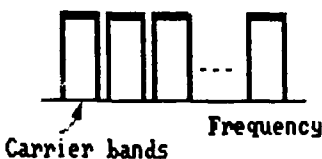
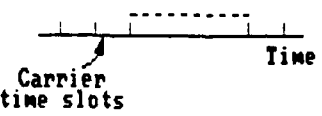
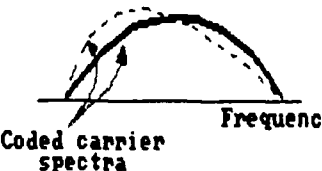
Multiple-access	Designation	Characteristic
Frequency division	FDMA	<p>Frequency separation</p>  <p>Carrier bands</p>
Time division	TDMA	<p>Time separation</p>  <p>Carrier time slots</p>
Spread spectrum	SSMA	 <p>Coded carrier spectra</p>

Figure 153. Basic Multiple-Access Techniques

the satellite transponder bandwidth. Separation of stations is achieved by frequency division. The entire uplink spectrum received by the satellite is frequency translated into the downlink. A receiving station receives the desired uplink transmitter by tuning to the proper channel in the downlink. Home TV satellite receivers are an example of FDMA. [Ref. 103:pp. 192-193]

(2) Demand-assignment Multiple Access (DAMA).

DAMA is similar to FDMA, but instead uplink frequencies are shared by many users. Individual frequencies are automatically assigned depending on user need and channel availability. DAMA systems can serve a greater number of users if each does not frequently access the satellite. DAMA systems are much more complex than FDMA systems because satellite and ground hardware are required to keep track of unused channels and assign frequencies to requesting stations. [Ref. 103:p. 193]

(3) Time Division Multiple Access (TDMA). With TDMA, all stations, whether transmitting or receiving, are part of a synchronized network. Uplink stations are separated in time rather than frequency, and a specific interval is assigned to each uplink station. TDMA uses very short digital bursts to accommodate many users. The decoding of each TDMA burst requires synchronization within each interval in addition to the network timing. TDMA is also more complicated than FDMA because of the requirement for system timing,

synchronization, and the assignment of unused time segments to requesting stations. [Ref. 103:pp. 229-233]

(a) Slotted ALOHA. This is a form of random access TDMA, where stations randomly transmit but only in synchronization with the system. Data collisions will only occur at certain times, and thus the channel's throughput is limited to about 36% of the channel's theoretical data capacity. Slotted ALOHA is more efficient than non-synchronized random-access systems, where capacity is limited to about 18% of the channel's theoretical capacity because collisions can occur at any time. [Ref. 52:pp. 528-539]

(4) Spread Spectrum Multiple Access (SSMA). As discussed above, SSMA carriers are separated by assigning specific PRN codes. Information is conveyed by mixing it with the specific PRN code and modulating the combined waveform onto the carrier. A station is able to use the entire satellite transponder bandwidth and transmit at any time. This allows the carriers to overlap. Carrier separation is achieved in the receiver by demodulating the proper PRN waveform. [Ref. 52:pp. 417-418]

#### c. Link Budgets

Geosynchronous satellite communication systems must be able to successfully send and receive signals over a 42,000 km (26,100 mile) slant-range path.

A link budget is used to calculate the system configuration and capacity. Elements of the link budget are

subject to physical laws, and they range from very large ( $10^7$ ) to very small ( $10^{-23}$ ) values. Link budget elements are multiplicative, so they are converted to decibels (dB) by the formula  $10(\log_{10}X)$ . This makes computation of link-budget performance easier by enabling elements to be added and subtracted from each other.

Given known physical and economic constraints, system design parameters can be computed and trade-offs analyzed. To determine if a given configuration will function, the positive and negative link budget data elements are added up. The sum must show a sufficient positive value or the system will not function as desired. Too low a margin shows one or more parameters will have to be varied. Too high a margin suggests the system may be inefficient because excess power or equipment capability is being used. [Ref. 52:pp. 365-368]

(1) Spreading Loss. A major portion of the link budget is the long-distance spreading loss. The wave front moving away from an antenna expands spherically. The surface area of a sphere is calculated as  $4 \times \pi \times R^2$ , where  $R$  is the radius. Because the transmitted power spreads out over larger areas as  $R$  increases, the density of the power per square area decreases as  $1/(4 \times \pi \times R^2)$ . This means that a one-watt signal, transmitted from a non-directional (isotropic) antenna, has a power density of 0.00000000000000004511 watts

per square meter (-163.5 dBW) at 42,000 km (the edge of Earth coverage). This is a tremendous reduction in signal strength and a major hurdle to be overcome in satellite communication system design. [Ref. 52:p. 221]

(2) Limited Satellite Downlink Power. Satellite downlink power can be the weakest link in the communication chain. Unlike earth stations which generally do not have a problem obtaining electrical power, communication satellites must function from solar cells. Satellite electrical power generation is a function of solar cell efficiency, amount of sun light exposure, and total cell area. The number of cells is limited because of weight and design constraints. This places an upward bound on maximum satellite transponder power. [Ref. 52:pp. 602-630]

(3) Other Elements. Other link-budget elements also reduce the signal-to-noise ratio. High data rates require greater signal strengths. The atmosphere absorbs a certain amount of RF, depending on the frequency and the weather. Background cosmic radiation, thermal RF noise radiated by the earth, and noise inherent in the receiver circuitry also act to mask the received signals. [Ref. 52:pp. 354-368]

(4) Overcoming Link Budget Deficits. One obvious way to overcome these limitations is to increase the RF power of the transmitted signal. Using a gain antenna focuses the RF energy into a narrow beam, increasing the effective

radiated power. A large surface area, high-gain antenna will increase the strength of the received signals. Use of a low-noise amplifier (LNA) allows the detection of very weak signals that would be masked by the internal circuit noise of a conventional RF receiving amplifier.

(5) Processing Gain. The use of data coding methods can provide additional gain to improve the link budget.

Error rates for all types of transmissions are determined by the signal-to-noise ratio at the receiver. In conventional modulation systems, a bit in error is a piece of information lost. An analogy is trying to listen in a crowd where the person speaking is occasionally drowned out by background noise. Once the information is obscured, there is no way to exactly recover it without the speaker repeating himself.

Digital data transmissions provide a way to increase the apparent signal-to-noise ratio. Most background noise is analog and randomly distributed. Special digital filters and processing circuits are able to remove random noise, as long as it does not exceed certain levels. Forward-error correction (FEC) can also be encoded into the digital data stream. This allows the receiver to recover lost data bits from the correctly received information, again as long as the missing data does not exceed critical amounts [Ref. 52:p. 416]. In spread-spectrum systems, information bits are

composed of many chips. An error results in the loss of only a chip. Since a bit can be reconstructed despite the loss of many chips, spread-spectrum systems have the ability to operate with lower signal-to-noise ratios than other types of modulations [Ref. 52:p. 519]. Processing gain is taken into account by the link budget and can allow operation of a system in cases where conventional modulation and bandwidth are inadequate.

#### d. Trends of Satellite Design

The early communication satellites were very simple in design and construction. They were spin-stabilized and used low-gain antennas which radiated a low-power, 360 degree doughnut-shaped beam into space. Only 17% of this beam struck the earth. A "brute-force" ground segment approach was used to overcome these satellite transmit and receive losses. Massive \$10 million, 30 meter, 63 dBi parabolic antennas (a gain factor of 2,000,000) were used. They were supplied by 3500 watt RF power amplifiers. [Ref. 104]

As launch vehicles became capable of lifting bigger and heavier payloads, successive generations of satellites were able to provide stronger down-link signals by using high gain directional antennas and much greater transponder power. Communications capacity increased through frequency reuse, utilization of higher frequency bands, and different modulation methods. Twenty-four years after the 1965 launch of Intelsat 1 (Early Bird), weighing only 85 lbs,



the link budget has been rearranged to allow the use of small earth antennas and power amplifiers of only a few watts.

Despite the high technology design and construction, communication satellites have essentially remained "dumb" signal repeaters. Future generations of satellites will be increasingly complex. Fixed and hopping spot beams will transmit and receive signals. Rather than simply transforming the uplink to a downlink, all received signals will be demodulated to baseband and routed through on board processors and digital switching circuitry. System logic will decide which spot beam will return the signal to earth. On board processing will allow the satellite to meet the needs of the user, rather than the user fitting in with the satellite. This will enable users with different equipment and capabilities to communicate directly via the "intelligent" satellite, which will automatically adapt to the signaling formats and rates of each user.

This concentration of complexity in the satellite will reduce the complexity and cost of the ground segment equipment. The expenses of the improved space segment, shared by many earth stations, will be more than offset by the reduced cost of the earth segment. [Ref. 105]

## F. SATELLITE RANGING

### 1. Theory

As shown in Figure 154, the expanding signal transmitted from a satellite is spherical in shape. The distance and elapsed time between any point on the wave front and the antenna is the same. The signal first strikes the Earth at a point directly beneath the satellite. When viewed from the satellite, the signal forms an expanding circle as it passes over the earth. Geometrically, this expanding circle is formed by the intersection of two spheres. Assuming the atmosphere does not distort the transmitted signal, and that the earth is perfectly smooth and spherical, at any instant all points on this circle are the same distance from the satellite.

If a transponder receives this signal and instantaneously relays it back to the satellite, the round-trip distance will be equal to the speed of light multiplied by the elapsed time. One-way distance will be half this amount. While this gives the range between the satellite and transponder, there is no way to determine where on the range circle the transponder is located.

As shown in Figure 155, if two satellites are used, then two range circles will intersect the transponder. Geometrically, the transponder lies at the intersection of three spheres. Two spheres are centered at the satellite locations with radii equal to the measured ranges to the

Satellite Ranging  
One Satellite

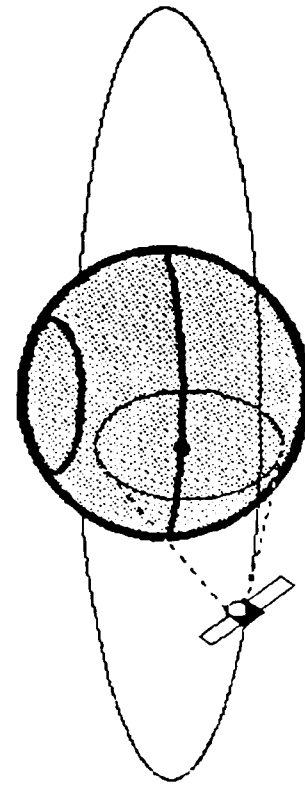
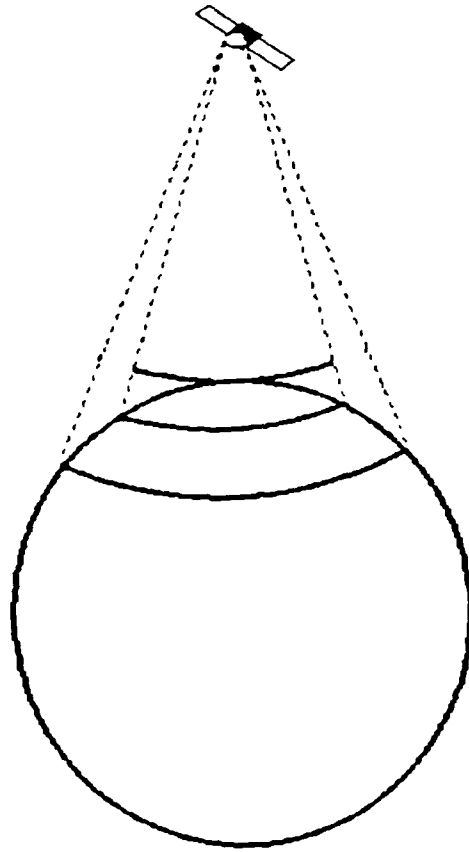


Figure 154. Satellite Ranging, One Satellite

# Satellite Ranging Two Satellites

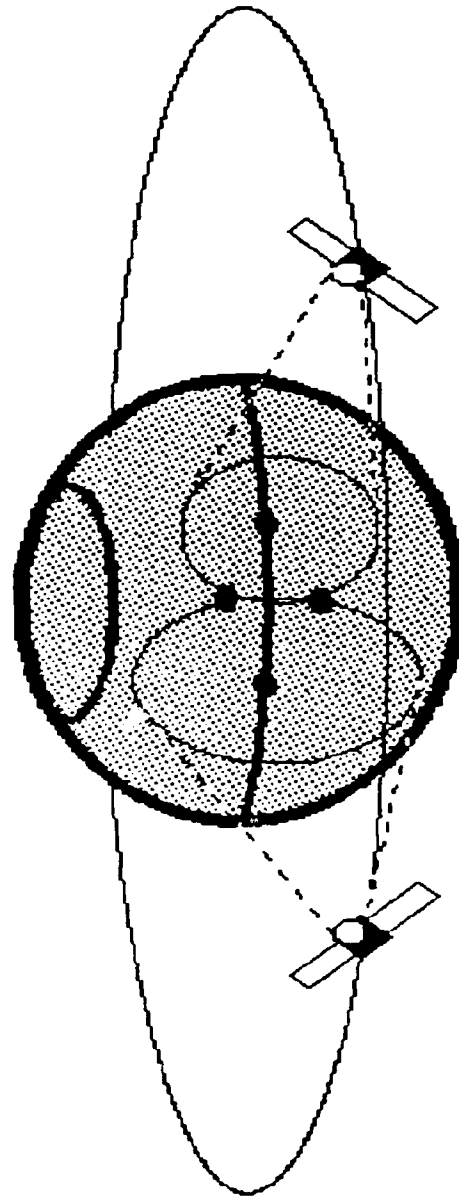


Figure 155. Satellite Ranging, Two Satellites

transponder. The third sphere is centered about the Earth's center with a radius equal to the Earth's radius. Knowing the exact position of the satellites with reference to the center of the Earth enables calculating the longitude and latitude of the two possible transponder locations. While still ambiguous, this solution can be used if the general location of the transponder is known. For example, tracking a vehicle using two geostationary satellites would produce a North and South solution. If the vehicle was known to be in the Northern hemisphere, then the Southern position could be discarded. [Ref. 106]

As illustrated in Figure 156, the addition of a third satellite will result in a single point fix as long as one satellite is not in the same orbital plane as the other two. This implies that one or more satellites are in a non-geostationary orbit. Here, the single point fix is the intersection of three-satellite range spheres. Use of three or more satellites enables the direct calculation of longitude, latitude, and height above the center of the Earth without reference to an earth sphere. Altitude above the geoid or ellipsoid (models representing the surface of the Earth) can be determined by subtracting the distance between the center of the Earth and the geoid or ellipsoid from the transponder's calculated height above the center of the earth. [Ref. 106]

Satellite Ranging  
Three Satellites

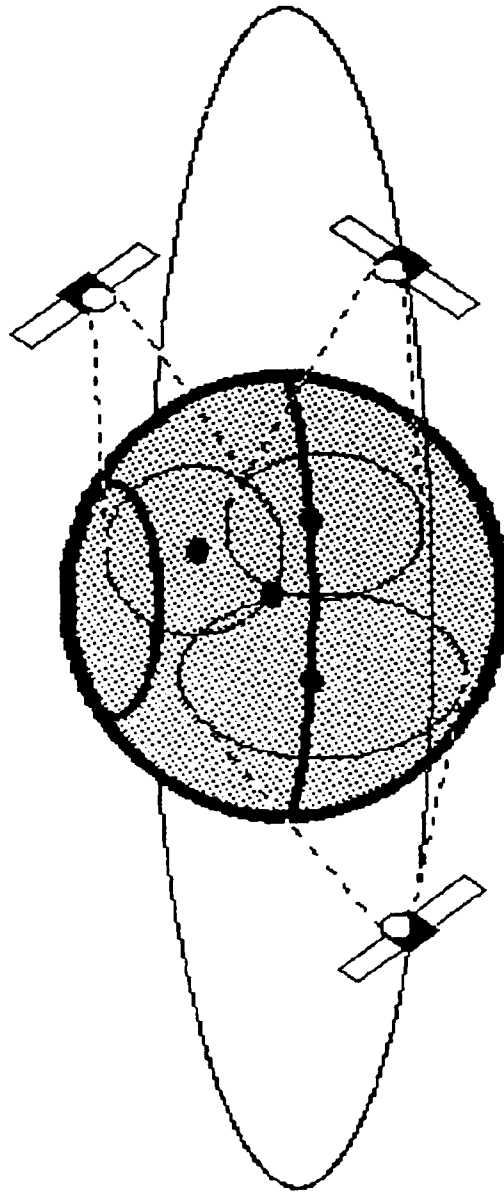


Figure 156. Satellite Ranging, Three Satellites

In reality, the satellite range spheres are not uniform. The earth's atmosphere slows down and bends the ranging signals. The amount of distortion is dependent upon several variables, such as the RF frequency and the angle at which the signal intersects the atmosphere. This distortion changes the signal travel time, and introduces range errors. Additional errors are introduced by the transponder reply delay and the difference between the calculated and actual satellite positions.

These errors can be reduced by mathematical modeling and the use of benchmarks. These are transponders dispersed over the area of coverage at precisely located sites. Their locations are computed from ranging data and compared with their known positions. Differences between the calculated and known locations are due to system errors and random variations. Mobile transponder position fixes are refined by applying the correction applicable to the nearest benchmark. [Ref. 8:pp. 36-58]

Position accuracy can be improved in a two-satellite ranging system by applying a correction to account for the irregularity of the earth's surface. This is because, as mentioned above, the position fix is calculated based on the intersection of the two-satellite ranging spheres and an earth sphere. An external altitude reference, such as a digital terrain map or an altimeter, provides a value to add to the geoid or ellipsoid to represent the true height above the

center of the earth. The effects of this correction are variable depending upon actual altitude and transponder location. [Ref. 8:pp. 43, 54]

Positioning accuracy is also a function of satellite geometry and range-timing precision. To improve position fix accuracy, orbits should be configured to create large crossing angles where the satellite range spheres intersect. Additional satellites can improve fix accuracy by providing additional range observations. Timing precision also determines fix resolution. An error of one millionth of a second can result in a ranging error of approximately 300 meters or 985 feet.

## 2. Tone Ranging

Tone ranging can be used on narrow-band satellite voice and data communication circuits. This enables satellite communication equipment to be used for ranging with a minimum of additional circuitry and costs. Experiments have shown accuracies of about 160 m (0.1 mile). [Ref. 8:p. 65]

Tone ranging is accomplished with analog or digital modulation.

### a. Analog

With analog ranging, one or more sinusoidal audio tones are modulated onto a carrier. Assuming no other propagation or transponder time delays, the distance traveled by the carrier during each audio cycle will be equal to the speed of light divided by the audio frequency. The signal is



sent from the ground station network management facility (NMF) via satellite to a ground transceiver, where it is retransmitted up to the satellite and back down to the NMF. As illustrated in Figure 157, the phase of the return signal is compared with the phase of the transmitted signal, and the difference computed. While it is not possible to tell the whole number of audio cycles in the round-trip path, the phase difference corresponds to the fraction of a wavelength which remains.

To eliminate the cycle-count ambiguity, additional low frequency, ambiguity-removal signals are transmitted. By comparing the phase angles of all return audio frequencies, it is possible to determine the whole-number cycle count of the primary ranging frequency. This can also be accomplished by coding the ranging signals at periodic time intervals. The number of whole and fractional wavelengths is summed and divided by the speed of light to give total round-trip ranging time. [Ref. 8:p. 66]

Range resolution is dependent on phase measurement accuracy and the audio frequency of the primary ranging signal. Benchmark transponders can be used to provide corrections for satellite position deviation, effects of the atmosphere on propagation, and delay through system electronics (except the ground transceivers). Standard values for delays introduced by ground transceivers are determined through engineering and actual testing. [Ref. 107]

## Tone Ranging

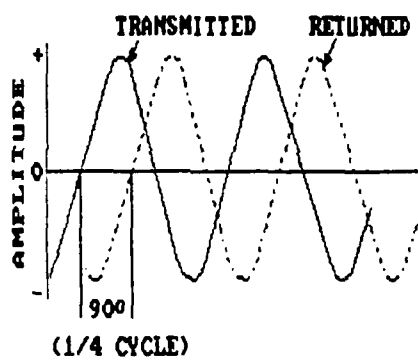


Figure 157. Tone Ranging

### b. Digital

Digital tone ranging is similar to analog, except that a rectangular waveform is used. The advantage of this method is that less ambiguity-removal signals are required.

A small portion of the rectangular waveform is coded and synchronized with a low-frequency, ambiguity-removal signal. The carrier is phase modulated by the digital signal. Comparison of return-signal coding with the ambiguity-removal signal indicates the whole number of rectangular waveforms in the round-trip path. A comparison of the phase difference between the transmitted and received rectangular waveform reveals the fraction remaining. [Ref. 8:p. 67]

### c. Multipath Effects

Analog and digital tone ranging are vulnerable to multipath effects. This occurs when part of the downlink signal is reflected by objects before reaching the transceiver. The transit time of the reflected signal is greater than that of the directly-received signal. This may cause range ambiguities by making it difficult to separate both signals.

Multipath tends to occur when satellite elevation angles are low. Multipath reception may be diminished by vehicle-antenna design and mounting location. Ambiguity effects can be reduced at the NMF by using electronic filtering to average the received waveforms. [Ref. 99:insert I]

### 3. Spread-Spectrum Ranging

#### a. Ranging

To compute the two-way distance, the NMF generates a PRN code signal which is relayed through the satellite to the ground segment. User transceivers synchronize and track this signal. Upon command the transceiver will send a different PRN-coded signal back through the satellite to the NMF. The NMF receiver acquires and demodulates the signal. Round-trip time delay is determined by comparing the phase of the receiver's PRN code generator to the phase of the transmitter's code generator that sent the command sequence.

Range ambiguity is dependent on the PRN-code repetition period. Range resolution is a function of the chip rate and the receiver's ability to track and measure fractions of a chip. As in tone ranging, bench-mark transceivers enable differential corrections to be made to transit time measurements. Adjustments to round-trip time are made by subtracting the known period between the time of transceiver reception and transmission. [Ref. 103:pp. 450-454]

#### b. Multipath

Spread-spectrum signals delayed by one chip or more will not correlate and therefore have little effect on the correctly received signal. This enables spread spectrum to be relatively immune to multipath effects from objects away from the immediate area of the receiver. Multipath effects from signals reflecting off nearby objects, such as a metal

car body, can result in a series of overlapping PRN chips slightly off-set from each other. This smears the signal acquired by the receiver, and can make precise tracking difficult. Antenna design and positioning can reduce this problem.

#### 4. Pseudo-ranging

In conventional two-way ranging, timing is controlled by only one clock. With one-way ranging, timing is controlled by a clock in the transmitter and the receiver. The transmitter clock generates the signal, and the receiver clock records when the signal arrives. The receiver "knows" when the signal was transmitted, and computes the propagation delay through subtraction.

As illustrated in Figure 158, one-way range in spread-spectrum systems is determined by the time shift required to line up a replica of the code generated in the receiver with the code generated by the transmitter. Assuming no other propagation delays, distance between the transmitter and receiver is equal to the elapsed time multiplied by the speed of light. Ideally, the time shift is the difference between the time of signal reception and the time of transmission. In reality, the two clocks will not be exactly synchronized, and a bias will be introduced into the time measurement. These biased time-delay measurements are termed pseudo-ranges. [Ref. 108:ch. 4, p. 12]

## Pseudo-range Measurements

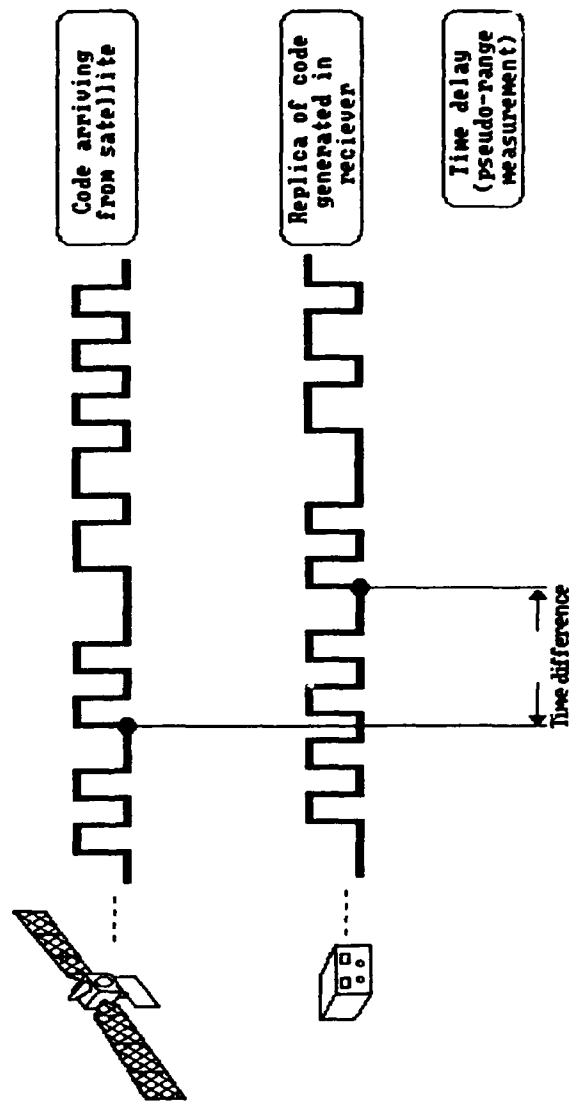


Figure 158. Pseudo-range Measurements

One-way satellite ranging systems use a transmitter on the ground and a satellite relay, or place the transmitter in orbit. In either case, ground stations measure the elapsed time and compute their pseudo-ranges from the transmitter. The STARFIX system generates spread-spectrum signals at its network management facility (NMF) and relays them to earth receivers via four geosynchronous C-band communication satellites [Ref. 109]. The U.S. Global Positioning System (GPS) and Soviet Glonass system generates spread-spectrum signals directly from orbiting satellites. In both cases, the ground user is able to compute his position through precision timing and knowledge of where each of the satellites are in orbit.

#### G. POSITION DETERMINATION SYSTEMS

Position determination systems which can be used to provide land-mobile location data for relay via satellite and HF communications systems are summarized in Table 32.

##### 1. Doppler Positioning

The Doppler effect is familiar to anyone who has heard the changing pitch of a moving source of sound, such as a train whistle or police siren. The pitch is high as the sound source approaches, drops markedly as the source passes, and maintains a lower pitch as it recedes. This same phenomenon holds true for electromagnetic radiation. Frequency is shifted when the transmitted and the receiver are in relative

TABLE 32

## WIDE AREA POSITION DETERMINATION PERFORMANCE [Ref. 110]

	<u>GPS (SPS-SA)</u>	<u>LORAN-C</u>	<u>TRANSIT</u>	<u>ARGOS</u>
METHOD	Satellite Pseudo-range	Hyper- bolic	Doppler	Doppler
ACCURACY (predictable)	100 m. horiz. 156 m. vert.	460 m	27-500 m	150 m to 9 km
ACCURACY (repeatable)	100 m. horiz. 450 m. vert.	18-90 m	15-27 m	N/A
ACCURACY (relative)	30 m. horiz. 46 m. vert.	18-90 m	11 m	N/A
FIX	3-D, time & velocity	2-D	2-D	2-D
FIX RATE	10-20/minute	10-20/min	1/hr (+/-)	6- 20/day
COVERAGE	Worldwide	Regional	Worldwide	World- wide
AMBIGUITY	None	Possible	None	Poss.
AVAILA- BILITY	99+%	99+%	99%	99%
1990 USERS (maritime)	Unk	450 K	95 K	Unk (4 K max)
DOD PHASE- OUT	N/A	1994	1996	N/A
DOT PLANS	Evaluate	2000 (Decision)	N/A	N/A

Note: Repeatable accuracy is the measure of the ability to return to a previous location using the navigation system. Relative accuracy is the ability to determine a geographic position from a navigation system.



motion because the amount of wave crests received per unit of time is changed. More wave crests are received when the transmitter and receiver are moving towards each other, thus the received frequency is higher. Conversely, when the transmitter and receiver are moving apart the received frequency will be lower.

The shift of frequency is dependent upon the relative speed between the transmitter and the receiver, and the angle formed between the receiver and the transmitter's path of motion. At any point along this angle the instantaneous doppler shift will be the same, but because of greater angular velocity, the rate of frequency change will be higher the closer the transmitter and receiver are together. As shown in Figure 159, this forms a cone with a satellite at its apex and the orbital track as its axis. The instantaneous frequency shift is identical anywhere on the cone, but the rate of change depends on the distance between the satellite and the receiver. [Ref. 8:p. 60]

When a satellite's orbit and speed are precisely known, it is possible to determine the location of the satellite at any instant in time. This, combined with the frequency and rate of the satellite's doppler shift, enables computing the slant-range distance between the receiver and the satellite. Since the satellite's azimuth and elevation from the receiver are not known, three or more observations are required during the same satellite pass to accurately

## Doppler Positioning

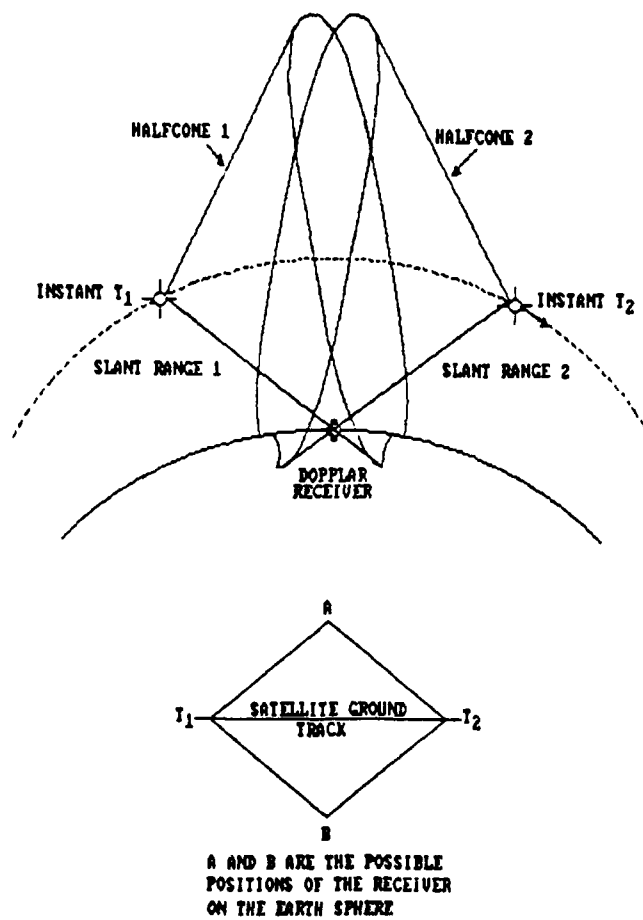


Figure 159. Doppler Positioning

determine the two possible position fixes. If the satellite is in a polar orbit, it is possible to resolve the ambiguity created by the symmetry of fixes on each side of the satellite track. This is possible because the earth's rotation also generates a doppler component that can be measured. [Ref. 113]

The transmitter carrier oscillator and the receiver local oscillator must be very accurate or errors will be introduced into the frequency-shift measurements. Motion on the ground can also affect the doppler measurement and accuracy. A ground speed of one meter per second (2.2 miles per hour) can lead to a location error of 200-300 meters (650 to 980 feet) when using a doppler satellite in a 850 Km (530 mile) orbit [Ref. 8:pp. 62-63]. Corrections can be made if speed and direction are known. The basic model used to determine position assumes all locations are at sea level. When on land, corrections for altitude above sea level must be applied to maintain position accuracy. Since doppler satellite coverage is not continuous, position fixes can only be made periodically. Estimated position between fixes can be determined by dead reckoning if speed and direction are known [Ref. 111].

a. Transit

The Transit Satellite system was designed by the U.S. Navy to enable position determination to within one-quarter mile. The first prototype Transit satellite was

launched in 1961. The classified system was declared operational in 1964. In 1967 the system was declassified and became available for general use. [Ref. 111]

In 1988 the system consisted of seven active satellites and four spares in circular polar orbit [Ref. 112]. As shown in Figure 160, the satellites have an altitude of approximately 1100 km (680 miles) and a period of 107 minutes. The transit satellites are controlled by the U.S. Naval Astronautics Group (NAG) at Point Magu, California. Four tracking stations in the U.S. serve as benchmarks for the system, gathering doppler data which are sent to Point Magu. The NAG computes each orbit from this data and extrapolates into the future. Twice each day these data are loaded into the satellite where they are stored for continuous broadcast. [Ref. 113]

Each satellite transmits on frequencies close to 150 MHz and 400 MHz. These two frequencies are used to enable the receiver to correct for atmospheric refraction effects and improve the position solution. Superimposed on both carriers is the satellite broadcast message which repeats itself every two minutes. From this message the satellite's instantaneous orbital position can be computed every two minutes or less, depending on the receiver sophistication.

The two received signals are compared with frequencies generated within the Transit receiver, and the doppler shift is computed over a time interval. The doppler

# Transit

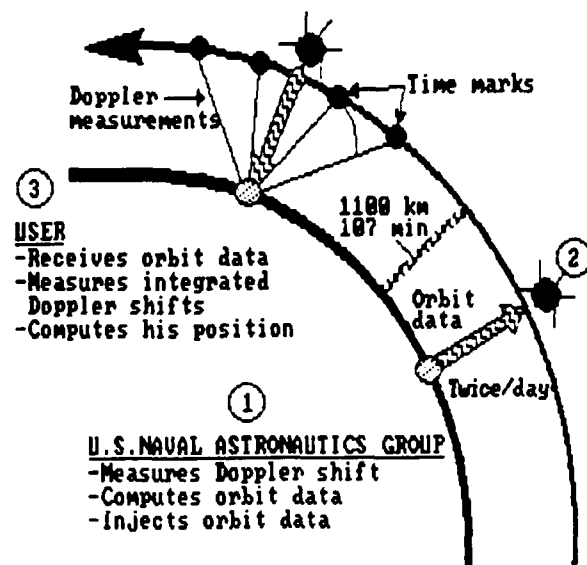


Figure 160. Transit

information is combined with orbit data and used to determine the slant range between the satellite and the receiver. At least three observations and slant ranges are determined to establish a position fix. To ensure an accurate fix, the receiver's velocity, heading, antenna height, and altitude above sea level must be input.

Since Transit satellites are in a low altitude orbit, they do not provide continuous coverage and position data. Dead-reckoning equipment is used to provide estimated positions when Transit satellites are not visible. [Ref. 113]

DoD intends to maintain the Transit system through 1996, when it will be phased out in favor of GPS. Popularity of the system and large-scale custom-integrated circuits enable lower accuracy single-channel Transit receivers to be sold at prices beginning at about \$1000. [Ref. 112]

b. Argos

Argos was used in Geostar System 1.0. Argos operates similar to Transit, except that the position of ground transmitters is determined by the doppler shift received by the satellite. The Argos system is a cooperative effort between the National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and the French space agency Centre National d'Etudes Spatiales (CNES). Argos receivers are located aboard NOAA/Tiros-N weather satellites which are in a 101-minute

circular polar orbit at an altitude of approximately 830 km (515 miles).

Argos ground transmitters periodically emit a 401.65 MHz formatted signal which carries sensor data. Message duration and transmission repetitions are randomly distributed within certain design parameters. The signal is received by a Tiros-N satellite and the doppler shift and sensor data are recorded for playback when in range of a tracking station. The downlinked Tiros-N satellite data is relayed to a NOAA processing center where the Argos data are separated and routed to CNES in Toulouse, France. CNES computes the position of the transmitter and decodes the sensor data. This information is subsequently passed to the user. [Ref. 8:pp. 59-65]

Depending on the frequency stability and ground speed of the transmitter, the Argos system is accurate to within several kilometers. Unlike Transit, Argos is unable to determine which side of the orbital track the transmitter is located on. This ambiguity can be resolved with multiple satellite observations, previous location information, or by using dead reckoning from the last known position. Up to 4000 transmitters can be handled by the Argos system, assuming they are randomly distributed over the Earth's surface. [Ref. 108:ch. 3, p. 7]

## 2. The Navstar Global Positioning System

### a. Definition and History

The Navstar (NAVigation Satellite Time and Ranging) Global Positioning System (GPS) is a satellite-based positioning system now being implemented by the Department of Defense. Work on the system began in 1973 as a result of the merger of the U.S. Navy's TIMATION Program and the U.S. Air Force's 621 B Project. Both of these programs were established in the mid-1960's to develop a worldwide, all-weather, real-time, passive navigation system using measured ranges from satellites. [Ref. 108:ch. 3, p. 8]

Eleven Block I GPS satellites were launched between February 1978 and October 1985 for test and evaluation purposes. There were not enough of these satellites to provide continuous worldwide coverage. As of January 1989 only seven of the original 11 Block I satellites remained operational. [Ref. 114]

The Challenger disaster and lack of alternate launch vehicles set the GPS program back several years. New Delta II missiles were obtained from McDonnell Douglas to augment the Space Shuttle. The current Block II schedule calls for the launching of six GPS satellites per year in 1989, 1990, and 1991, with the last three to be orbited in 1992. Initial operational capability (IOC) will be in late 1990 when 12 satellites will provide continuous two dimensional (longitude and latitude) coverage. Full



operational capability (FOC) providing three-dimensional coverage is scheduled for 1992<sup>4</sup>. The first Block II satellite was launched by a Delta II on 14 February 1989.

b. System Overview

(1) Satellite segment. When fully operational in early 1992, GPS will consist of a constellation of 24 operational satellites (21 plus three operating spares). As shown in Figure 161, these satellites will be in six orbital planes inclined 55 degrees to the equator and have approximately 12-hour, 20,230 km (12,570 mile) orbits. This configuration allows the simultaneous visibility of five to 11 satellites at any time almost anywhere in the world. [Ref. 114]

(2) Control Segment. The control segment includes a master control station (MCS) located at The Consolidated Space Operations Center in Colorado Springs and five other monitor stations spread around the world. The control segment monitors the health of the satellites, determines their orbits and the drift of the atomic clocks, and updates the broadcast navigation message transmitted by each satellite. [Ref. 108:ch. 4, p. 9]

(3) User Segment. The user segment consists of military and civilian users. User equipment is designed to receive and process the signals from satellites which are in view from the receiver's location. The receiver processor

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<sup>4</sup>Telephone conversation between Ltc Overtuff, GPS project officer, U.S. Space Command, and the author, 6 February 1989.

## GPS Satellite Constellation

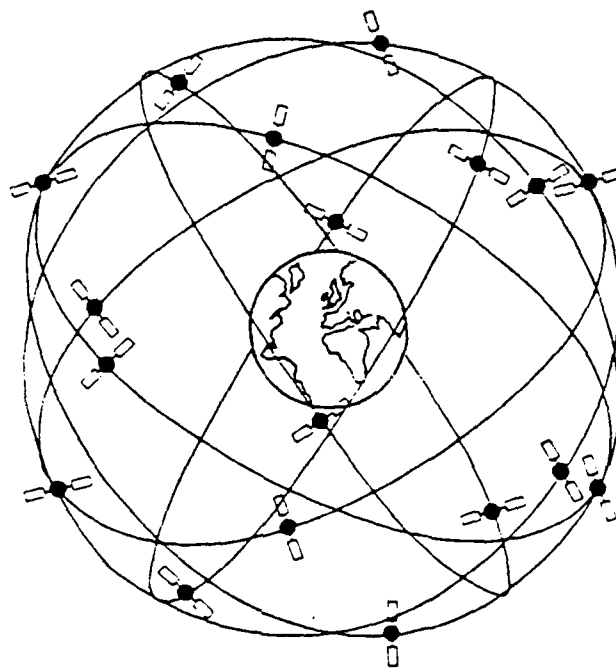


Figure 161. GPS Satellite Constellation

converts the received signals from three or more satellites into highly accurate time and position data. [Ref. 115]

c. Basics of GPS Position Determination

GPS uses one-way ranging for the determination of user position. Highly accurate receiver clocks are not needed because precise time is also derived from the solution. A minimum of three GPS satellites are required to determine longitude and latitude. Four or more satellites permit accurate altitude measurement. [Ref. 114]

(1) GPS Satellite Position. As in other satellite ranging and doppler systems, the orbital location of each visible GPS satellite must be known to enable solving for the variables of position and time. Each GPS satellite modulates a low data-rate (50 bits per second) navigation broadcast onto the 1575.42 MHz  $L_1$  and 1227.6 MHz  $L_2$  frequencies. This broadcast provides the receiver with ephemeris data to determine each of the satellite's positions, the time corrections to make to each satellite's clock, the operational status of each satellite, and other information. [Ref. 108: ch. 4, p. 10]

(2) One-way ranging. GPS one-way ranging is electronically much more complicated than the two-way satellite ranging discussed above, although much of the concept is the same. The major difference is signals are only transmitted one-way from the satellite to the ground receiver.

This requires extremely precise, synchronized time between all satellites and receivers. An error of one microsecond (millionth of a second) equates to a distance of 300 meters (985 feet).

Each GPS satellite is equipped with atomic clocks. Although extremely accurate, each atomic clock will drift very slightly and thus keep different time. Since it is not practical to physically synchronize all the atomic clocks, they can be mathematically synchronized by adding or subtracting the amount of drift. This is achieved by ground stations monitoring the differences in GPS clock-signal timing. Mathematical corrections are periodically uploaded by the Master Control Station into the GPS satellites for continuous rebroadcast in the navigation message. Users can then assume that all GPS ranges measured by their receiver are related to the same (fictitious) clocks aboard each of the satellites. [Ref. 108:ch. 4, p. 12]

The clocks aboard each satellite control the generation of two unique pseudo-random noise (PRN) spread-spectrum transmissions. The receiver knows the different PRN sequences of each satellite in the constellation. The receiver's clock synchronizes the generation of the local PRN sequence with the satellite's PRN sequence. When the signal is first received it will not correlate with the locally-generated PRN code because of the propagation delay. The local PRN code is shifted in intervals until correlation is

achieved. Tracking is maintained to a fraction of a chip. The time difference in shifted PRN chips multiplied by the velocity of light, and corrected for atmospheric effects, will equal the distance between the transmitter and receiver. This is known as the pseudo-range. [Ref 108:ch. 4, p. 14]

(3) Carrier Phase Ranging. Carrier phase measurement is a more precise method of determining range to the GPS satellite. Although it is not possible to directly measure the integer amount of frequency wavelengths between the satellite and the receiver, a phase measurement can determine what fraction of a wavelength remains. This information is combined with other distance calculations to increase the range accuracy. Carrier phase-ranging is only used in precision survey work and is not used in mobile applications. [Ref. 108:ch. 4, p. 15]

#### d. GPS Signal Characteristics

GPS signals are modulated by two PRN codes. The coarse acquisition (C/A) code and the precision (P) code are repeating PRN sequences unique to each satellite. Spread-spectrum modulation is used to prevent jamming and permit more accurate range measurements.

The C/A-code, transmitted only on the  $L_1$  frequency at a 1.023 MHz PRN chip rate, allows position determination with an accuracy of approximately 60 meters (200 feet) horizontally and 100 meters (330 feet) vertically. The P-code

is broadcast on the  $L_1$  and  $L_2$  frequencies at a chip rate of 10.23 MHz. This is the most precise service and is accurate to approximately 18 meters (60 feet) horizontally and 28 meters (92 feet) vertically.

The difference of code rates and frequencies is significant. The higher code rate of the Precision Positioning Service (PPS) provides ten times the range resolution of the C/A-code Standard Positioning Service (SPS). The use of both frequencies by PPS improves the ability to correct for atmospheric propagation effects and reduces positioning errors.

The C/A code is generated by unclassified circuits and equations. The equations and circuitry which generate the P-code are classified and permit only authorized users (generally U.S. and Allied forces) to obtain the most accurate GPS position information [Ref. 108:ch. 4, p. 10]. When GPS becomes operational, the SPS will be intentionally degraded (Selective Availability) to limit the horizontal accuracy to 100 meters (328 feet) and 156 meters (511 feet) vertically [Ref. 114].

#### e. General GPS Receiver Operation

When the receiver is turned on it first enters a self-test mode. The receiver then searches for and locks on to the C/A-code of one visible GPS satellite. The navigation broadcast data are collected, and the receiver's clock is

initially set from message-timing data. The signal travel time is estimated. The receiver continues its search until at least four satellites are found and their navigation data are collected. The first receiver position is then computed using initial time measurements from these satellites. The computed position will be off due to the clock setting inaccuracy. Using this first position, the receiver's clock timing will be adjusted and another round of timing measurements taken. The calculated positions and times will converge over several iterations to the correct value. From this point on the receiver will continue measuring pseudo-ranges and updating position and receiver timing. This subsequently enables the receiver to compute and display velocity and heading information. [Ref. 116]

f. Accuracy When Used for Land Vehicle Navigation

The U.S. Department of Transportation conducted GPS road and highway tests in Massachusetts. A drop in signal strength was noted when passing under overpasses, bridges, and in high foliage areas. However, the GPS receivers continued to track unless the vehicle stopped under structures. The only major problem was the blockage of GPS signals in downtown Boston. The GPS receivers were unable to maintain an accurate navigation position when driven through areas where the streets were flanked by high rise buildings greater than ten stories. Placing a receiver in an altitude hold configuration, which requires only three satellites for a

two-dimensional fix, improved the position accuracy on certain downtown runs.

A 30-minute interval GPS Block II visibility profile was developed for the Boston area. The analysis shows that continuous visibility of four satellites at this latitude (approximately 42.5 degrees North) requires an unobstructed horizon to the 20 degree level. Three or more satellites are continuously visible if the receiver has an unobstructed horizon to 30 degrees. The authors concluded that using GPS for navigation in high skyline areas will require dead-reckoning equipment to provide estimated positions when satellites are blocked. [Ref. 117]

e. GPS Receiver Cost and Availability

Single-quantity GPS receivers cost between \$3000 and \$25,000, depending on their features<sup>5</sup>. Part of the reason for this cost is that GPS is pending full implementation, the electronics are complex, and the production volume of GPS receivers has been small.

Several manufacturers have developed specialized GPS Very-Large-Scale Integrated circuits (VLSI chips) which dramatically reduce the receiver parts count and cost. In 1988, one manufacturer offered a basic single-channel receiver for \$3000 [Ref. 61]. As the Block II constellation takes shape, GPS receiver demand and production economies of scale

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<sup>5</sup>Interview between Mr. Tom Carpenter, independent marine electronics engineer, and the author, April 1989.



will increase. It is expected that hand-held GPS receivers will eventually cost less than \$1000 [Ref. 108:ch. 4, p. 29]. The Director General of INMARSAT has predicted that in the early 1990's it would cost only a few hundred dollars to add a set of GPS chips to a mobile satellite terminal for full position determination and reporting capability [Ref. 61].

#### 4. Glonass

The Soviet Glonass system is similar in concept to GPS. The system is designed to provide position measurements accurate to within 100 m horizontally and 150 m vertically. Like GPS, Glonass uses two L-band frequencies modulated by a C/A code and a P code. The major difference is that whereas GPS satellites all use one frequency pair but different codes, Glonass satellites transmit on different frequencies but use the same codes. The Soviets have stated they will make Glonass available for public use [Ref. 67:pp. 273-275].

#### 5. Loran-C

##### a. Definition and History

Loran stands for Long Range Navigation. Loran was developed during World War II for the precision radio-navigation of ships and aircraft. The first system, Loran-A, was in use from World War II through the early 1970's. Loran-B was an experimental system designed and tested in the 1950's. This system had so many technical problems that the project was canceled. Loran-A was succeeded by Loran-C. Loran-C offers increased navigational accuracy, reduced

interference, and a larger geographical coverage area. [Ref. 118:ch. 2, pp. 9-13]

b. Theory of Operation

Loran-C operates in the low-frequency spectrum of 90 to 110 KHz with a carrier frequency of 100 KHz. Loran-C consists of transmitting stations arranged in groups forming a loran chain. Three to five transmitting stations make up a chain. The station in the center of the chain is designated the master while the others are called secondaries. The chain coverage area is determined by the power transmitted from each station, the distance between the stations, and the physical orientation of the chain.

Loran-C relies on two basic principles: radio waves travel at a constant speed and the location at which the signals are received is directly proportional to the elapsed time between the transmission and the reception of the signal.

Loran-C determines location through the use of constant time difference line of positions (LOP's). These LOP's are plotted on a navigation chart as hyperbolas. A hyperbola is a line generated by a point so moving that the difference of the distances or times from two fixed points is constant. Hyperbolas from a Loran master and secondary are illustrated in Figure 162 [Ref. 118:ch. 4, p. 57].

The Loran-C master station transmits a series of coded pulses, and after a specified period of time each of the secondary stations also transmits a series of coded pulses.

## Loran-C Hyperbolic Lines of Position

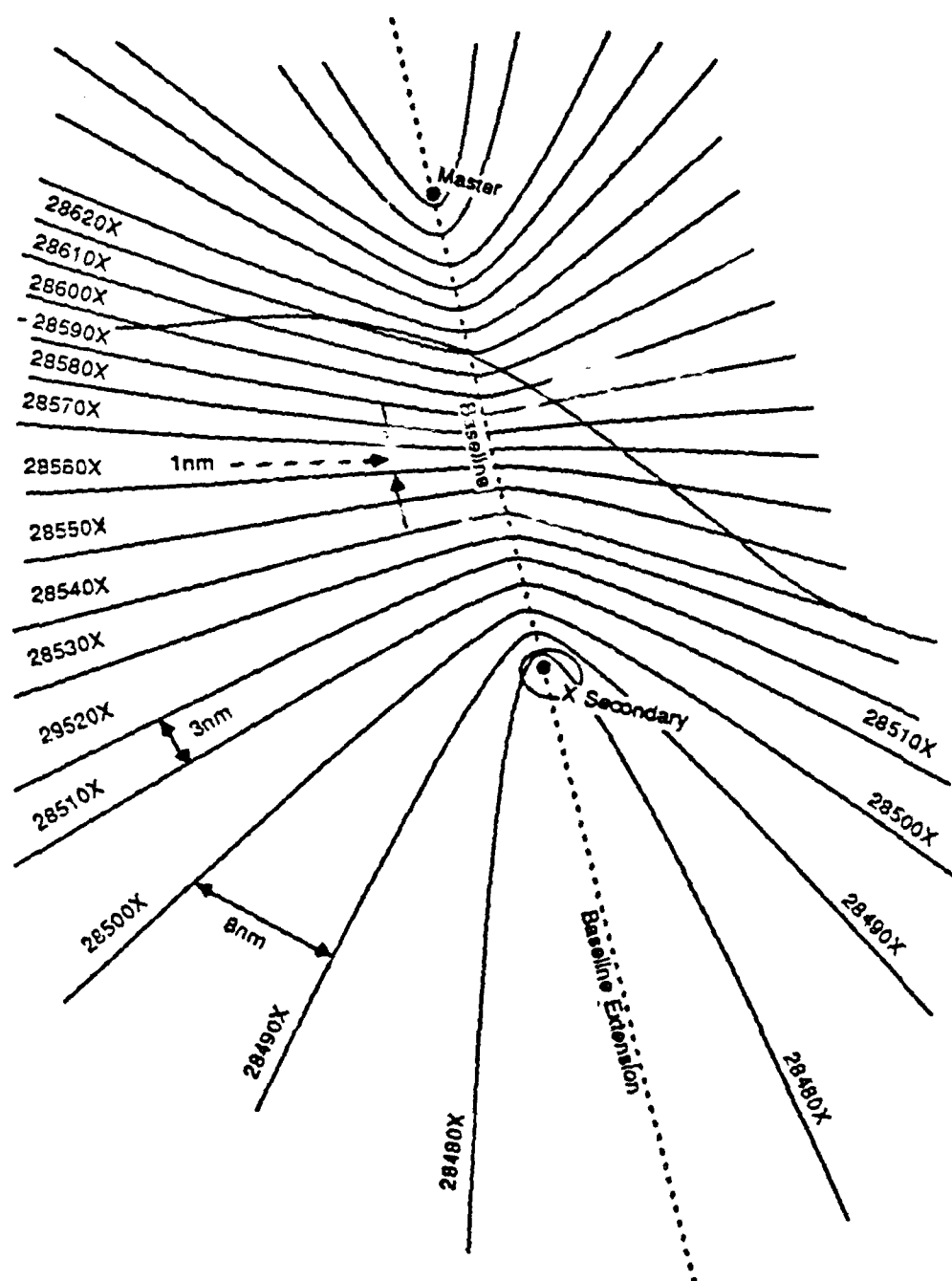


Figure 162. Loran-C Hyperbolic Lines of Position

The time lag is different for each secondary station. The coded pulses identify each loran chain station and provide other information. The Loran-C receiver measures the difference in time it takes to receive the signals from a master and secondary station. The time difference (TD) is measured in microseconds (millionths of a second). This TD is constant along the hyperbolic LOP, and by itself provides no absolute position information.

To determine position, at least one other LOP must be developed. To do this, the Loran-C receiver measures the TD between the master and a different secondary station. This establishes a second hyperbolic LOP. Where these two LOP's intersect is the receiver's position. Loran-C chains are configured so that at least two LOP's are available for any point within the coverage area. [Ref. 118:ch. 4, pp. 1-86]

Traditionally, the plotting of fixes has been a matter of interpolating the measured TD's between the standard hyperbolic TD's overprinted on a navigation chart. These standard TD's are plotted in ten microsecond (millionths of a second) intervals. Once the fix is plotted, longitude and latitude can be read from the chart.

This manual procedure can be performed electronically to provide a direct reading of longitude and latitude. This is accomplished by building a small computer into the Loran-C receiver which "knows" the locations and other specifications of the Loran-C chains. The computer measures

the TD's, computes the intersection of LOP's, and calculates the longitude and latitude. This information is digitally displayed. [Ref. 119:p. 33]

c. Propagation of Loran-C Transmissions

Loran-C signals propagate from the transmitter by groundwave and skywave. Loran-C is designed to primarily use the groundwave signal. Groundwave transmissions travel at a constant velocity over water, but vary in speed over land. This characteristic can change the time difference (TD) and effect land-position fix accuracy. Skywave transmissions may be used outside Loran-C coverage areas where groundwave reception is not possible, but navigational accuracy will be reduced. This is because skywave transmissions reflect off the ionosphere rather than travelling a direct path from the transmitter to the receiver. The varying ionospheric height, reflection angle, and intensity of reflection are variables which affect the skywave TD. A skywave may arrive at a receiver as little as 35 microseconds or as much as 1000 microseconds after the ground wave would have. Specialized signal-shaping and phase-change patterns are used to prevent the skywave signals from causing interference received ground wave signals. [Ref. 119:pp. 76-77]

d. Loran-C Coverage Areas

Loran-C groundwave propagation enables reliable survey and mathematical prediction of time difference lines of position over wide service areas. Service areas are defined

as the portion of the Earth's surface over which the signal parameters of a station-referenced system, as affected by geometry and nature, remain within specified tolerances at least 95% of the time. These tolerances are a 3:1 Signal-to-Noise Ratio groundwave coverage and a 460 m (1/4 nautical mile) or less predictable fix accuracy. [Ref. 119:p. 82]

(1) Current Coverage. Loran-C coverage is provided in the Continental United States, Alaska, and Hawaii. Additional maritime service areas are located on the East and West Coasts of Canada, and in areas of the North Atlantic, Norwegian Sea, the Mediterranean, and Northwest Pacific. Only the Continental U.S. service areas will be discussed.

Loran-C covers the East and West Coast waters (the coastal confluence zone) of the Continental United States out to several hundred miles. Inland coverage on the West Coast extends over Oregon, Nevada, Utah, and most of Washington, Idaho, and California. Inland coverage on the opposite side of the U.S. extends Eastward from a line running approximately through mid-Minnesota to the southern tip of Texas.

The inland area of the U.S. that is not contained within any Loran-C service area extends roughly from mid-Washington Eastward to mid-Minnesota, and southward to Arizona, New Mexico, and Texas. This area is referred to as the mid-continent gap. Loran-C service in this area is less accurate than the 1/4 nautical mile specification. Reception

relies on a combination of groundwave and skywave signals and contain LOP crossing angles of less than 30 degrees. This adversely effects position accuracy. [Ref. 119:pp. 59-67]

(2) Future coverage. The popularity of Loran-C for aircraft use, the availability of relatively inexpensive Loran receivers, and the delay in implementing the Global Positioning System (GPS) have prompted the U.S. Government to expand the Loran system to eliminate the mid-Continent gap. The Midcontinent Loran-C Expansion Project is expected to be completed by the beginning of 1991 at a cost of \$40 million<sup>6</sup>. Figures 163 and 164 illustrate the placement of the new Loran-C chains. [Ref. 120]

e. Accuracy at Sea

As stated above, the minimum predictable accuracy within the service area is 460 m (1/4 Nautical Mile). Accuracies higher than this are typically experienced when used at sea. Repeatable and relative accuracy typically range from 18-90 m (60 to 300 ft). [Ref. 110]

f. Accuracy When Used for Land Navigation

(1) Additional Secondary Phase Factor. Loran-C ground-wave signals propagate at constant speeds over water, but travel at varying speeds over land. This phenomenon is known as the additional secondary-phase factor, and is

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<sup>6</sup>Telephone conversation between Ens Barnet, Radio Navigation and Applications Branch, U.S. Coast Guard, and the author, February 1989.

PREDICTED LORAN-C GROUNDWAVE COVERAGE  
 NORTH CENTRAL U.S. (CLINT (MOUSS))  
 D-25 MALLICA 13 MILE 200MS  
 SWR - 1000 NOISE 5.0M ABOVE 10V/H  
 PWP (400) - LIBERTY (400), CASPER (400)  
 EXISTING LORAN-C PWP FROM  
 BALDWIN HALL STILES (1984, G-MNH)  
 CONDT (G-1ES-3) USCG  
 SIN 07-00Z (MPT) 27 FEB 02  
 CK 10-25-04 APP. 4-1-11  
 J. MCNEVER  
 LTJG D.B. BETTS

Figure 163. North Central U.S. Loran-C Chain



# South Central U.S. Loran-C Chain

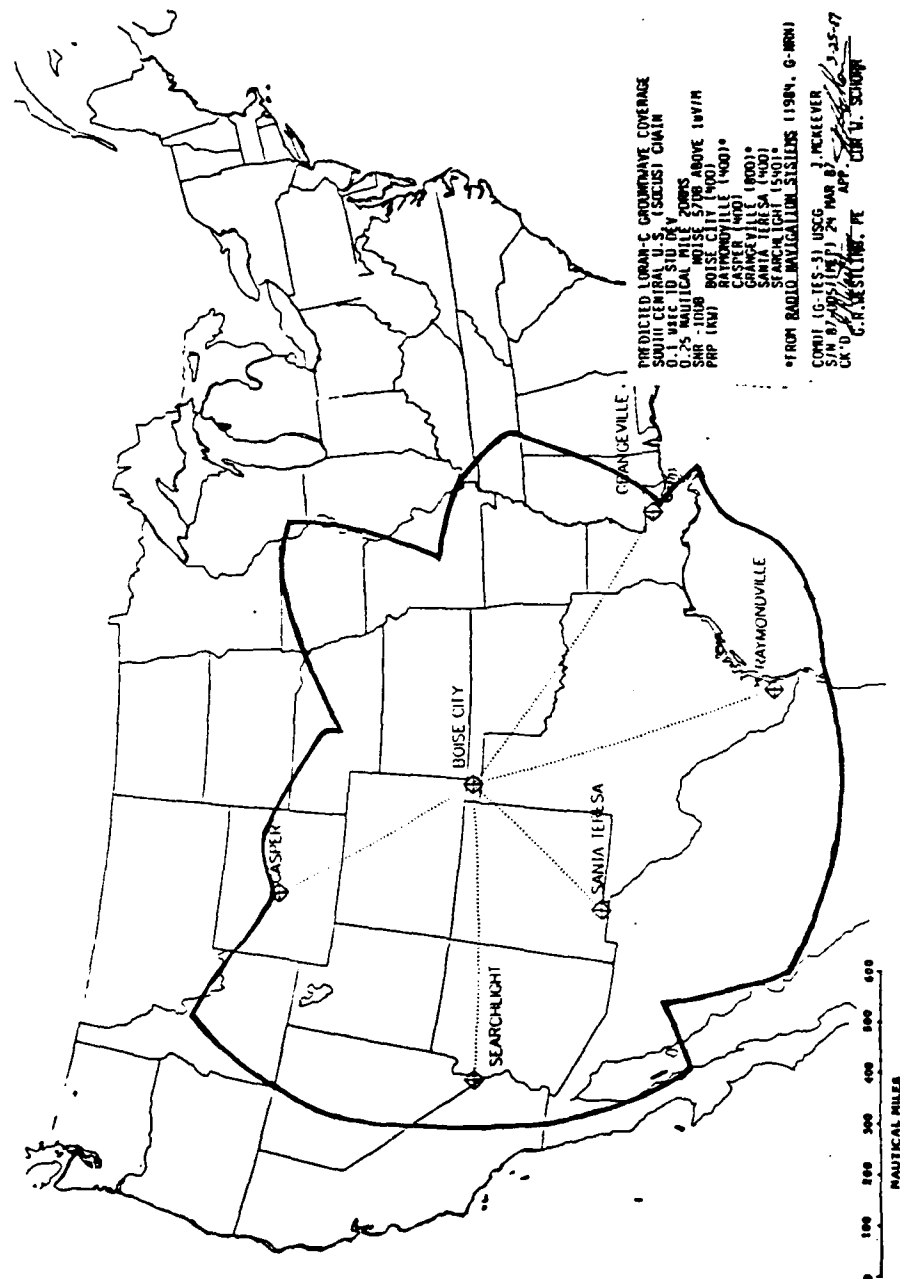


Figure 164. South Central U.S. Loran-C Chain

measured in microseconds. This is the time difference that an actual Loran-C signal, which has traveled over varied terrain, differs from an ideal signal which has been predicted for travel over an all-seawater path. Additional secondary phase factors can be measured and calculated, and their effect is taken into account when making nautical charts. Latitude-longitude conversion circuits in Loran receivers designed for sea navigation generally use equations that compute position based on an all-seawater path between the transmitters and the receiver. When used on land this degrades the position accuracy. Applying an average secondary-phase correction factor for an all-land groundwave signal may improve the accuracy of receiver position calculations, but the results will not be as accurate as theoretically possible. This is because each type of terrain, such as mountains, desert, snow, lakes, farmland, and urban areas effects groundwave propagation differently and effects the TD. [Ref. 119:p. 28]

(2) Power-Line Interference. Power-line noise and power-line carrier-communication systems can interfere with the reception of Loran-C signals. This is not generally a problem when briefly driving under a power line because the Loran receiver positioning-determination process averages many Loran pulses. However, a Loran-C experimenter found that driving parallel to a large power line for a mile or so can cause a receiver to lose track of Loran transmissions or

display an erroneous position. Driving near a power station also produced the same effects. [Ref. 121]

(3) Highrise Effects. Clusters of highrise buildings can cause a reduction of signal strength, an increase in background radio noise levels, and a general distortion of the TD and signal waveform. This will affect position-determination accuracy. Fortunately, this problem is limited to a relatively small region within cities. [Ref. 122]

(4) Operation in the Midcontinent Gap. As stated above, operation of a Loran-C receiver outside of the service area will result in greater position errors. Unsuitable Loran chain geometry, reduced signal strength, the spreading of the hyperbolic lines of position (LOP), reduction of the LOP crossing angles used to determine a fix, and the time delays associated with skywave propagation will also reduce position accuracy. These effects are not possible to accurately quantify because of the many variables. This will cease to be a problem for the continental U.S. when the Midcontinent Expansion Project is completed by the end of 1990. [Ref. 120]

g. Loran-C Receiver Cost and System Continuation

Specialized VLSI chips and production economies of scale enable Loran-C receivers, which automatically display longitude and latitude, to be sold on the retail market for

between \$400 and \$2000<sup>7</sup>. Because of the large user base (estimated at 450,000) and the delay in implementing GPS, the Department of Transportation will fund Loran operation through at least the year 2000 [Ref. 110].

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<sup>7</sup>Interview between Mr. Carpenter, independent marine electronics installation engineer, and the author, April 1989.

## APPENDIX C

### MOBILE COMMUNICATIONS COST/BENEFIT SPREADSHEET

#### A. STRUCTURE

The template is divided into several major and minor sections. These are listed in the Macro Menu area at the top of the spreadsheet. Macros will automatically move the user to the desired area. The "Home" key is used to return to the Macro Menu from any location.

Motor-carrier expenses, revenues, operating statistics, and the assumed benefits and costs of a nationwide tracking and communication systems are applied against the purchase and installation cost of the fixed and mobile equipment. Lease and financing options are not performed. The spreadsheet analysis assumes the firm is federally taxed at the highest rate and that earnings are sufficient to take full advantage of depreciation writeoffs. State tax and depreciation schedules are not included. The template accounts for tax effects and depreciation over six and eight-year periods using the IRS five and seven-year Modified Accelerated Cost Recovery System (MACRS) and the optional straight line methods. The yearly depreciation percentages are based on a midyear convention [Ref. 46]. The useful economic life of the equipment is expected to be the length of the depreciation period. Disposal value is assumed to be zero. Inflation

factors are not included. The model evaluates the cash flows under the regular payback, net present value (NPV), and internal rate of return (IRR) procedures.

A sensitivity analysis is also performed for each type of investment evaluation method to enable the user to gauge the effects of cash flow changes. The tabular results of the sensitivity analysis can be displayed as a graph by using the appropriate macro command.

#### B. DATA INPUT

The Cash Flow Effects section of the spreadsheet utilizes detailed carrier operating data, costs, expenses, and assumptions about the benefits and costs of RDSS and LMSS. The user inputs this information in the "Required" column and the spreadsheet computes the monthly cash flow per equipped vehicle. When each subsection is completed the result is also displayed in the Monthly Summary per Unit section at the top of the spreadsheet.

The calculations and assumptions made in the template are self-explanatory except for driver and equipment productivity and deadhead avoidance. Although in reality these categories are interrelated, the spreadsheet treats them separately. The model measures the effect of deadhead avoidance by increasing the percentage of loaded miles driven. The additional loaded miles are multiplied by the contribution margin per mile

(revenue minus variable costs) to derive the amount of expense savings or additional gross profit.

Input for the driver and equipment productivity calculation is based on the additional hours per month that the vehicle can be operated. Driver and equipment productivity increases are measured by the model as the added loaded distance, above the amount computed in the deadhead reduction category, that the vehicle is able to travel during a one-month period. The additional loaded miles are determined by multiplying the total extra distance traveled by the revised loaded mile percentage taken from the deadhead avoidance category. The additional loaded miles driven are multiplied by the contribution per mile to give the impact on operating profits or expenses. The calculated increases in both categories are then added together to give the total impact on operating profits or expenses.

The user can bypass the Cash Flow Effects section and place values directly into the Monthly Summary per Unit. Users are reminded this will break the cell links between these two sections and are cautioned to ensure a back-up copy of the original spreadsheet template is maintained.

Costs of the equipment and installation are inserted in the Cash Flow and Present Value section. The user's marginal tax rate and the discount rate are required in the Discounted Cash Flow Analysis section. The user is also required to

provide an initial guess, of the IRR to perform the IRR analysis.

C. SOURCE

The template is written in Borland Quattro, but can be converted to Lotus 123 and Symphony formats. A copy of the spreadsheet in any of these formats is available on a 360K disk from:

Lcdr W. J. Schworer  
3023 Gayla Court  
Spring Valley, Ca 92078



# MACRO MENU

HOME Return to Macro Menu

## FINANCIAL ANALYSIS

ALT A Cash Flow & Present Value  
ALT B Payback Period  
ALT C Discounted Cash Flow  
ALT D Present Value Summary  
ALT E Internal Rate of Return

## CASH FLOW EFFECTS

ALT F Revenue and Cost Information  
ALT G Premium Service Revenue

## EXPENSE REDUCTIONS

ALT H Deadhead Reduction  
ALT I Driver and Equipment Productivity  
ALT J Layover Pay  
ALT K Dispatcher Productivity  
ALT L Safety, Security, and Insurance  
ALT M Administrative Expense  
ALT N Telecommunications Expense

## COST INCREASES

ALT O Monthly Service Charges  
ALT P Telecommunication Expense  
ALT Q Maintenance Expense

## GRAPHS

ALT R Payback Period  
ALT S NPV Sensitivity  
ALT T IRR Sensitivity

## MONTHLY SUMMARY PER UNIT

Note: Figures are automatically inserted when the appropriate modules are completed.

	Net per month
Revenue:	
Premium service contribution	\$0.00
Miscellaneous	0.00
Operating Efficiency:	
Deadhead avoidance	\$131.54
Driver productivity	123.08
Layover Pay	0.00
Dispatcher productivity	0.00
Security, Safety, Insurance	0.00
Administrative expenses	0.00
Miscellaneous	0.00
Telecommunications Expenses:	
Reduction of expenditures	\$38.80
Miscellaneous	0.00
Subtotal: Gross increases	\$293.42
Less:	
Monthly service charge	\$150.00
Equipment lease expenses	0.00
Nationwide pager service (if used)	0.00
Monthly charge for communication with the network management center	1.76
Maintenance	4.17
Miscellaneous	0.00
Total Expenses	155.93
Gain / (Loss) per unit per month	\$137.49

# CASH FLOW AND PRESENT VALUE MODULE

Note: This module performs a discounted cash flow analysis and includes income tax and depreciation effects. Depreciation is figured under both the 5 and 7 year MACRS schedule and the alternate straight line method in accordance with IRS pub 534 (Rev. Dec. 87).

TOTAL CAPITAL OUTLAYS	REQUIRED INFORMATION	COMPUTED TOTALS
REQUIRED INFORMATION		
Number of units installed	446	446
Cost of equipment per unit	\$4,500	\$2,007,000
Cost of installation per unit	100	44,600
Cost of software package	3,000	3,000
Cost of additional ADP/HIS equipment		0
Miscellaneous	0	0
SYSTEM TOTAL COST		\$2,054,600

Total system cost per unit \$4,607

PAYBACK PERIOD ANALYSIS	COMPUTED
System Total Cost	\$2,054,600
Total Gain (Loss) per Month	\$61,319
Payback Period in Months	33.5
Payback Period in Years	2.8

## PAYBACK PERIOD SENSITIVITY ANALYSIS

	AMOUNT	PAYBACK PERIOD IN YEARS	EQUIVALENT ADDITIONAL LOADED HILMS
MONTHLY CASH FLOW GAIN PER UNIT AFTER ALL EXPENSES:	\$0	N/A	0
	20	19.2	77
	40	9.6	154
	60	6.4	231
	80	4.8	308
	100	3.8	385
	120	3.2	462
	140	2.7	538
	160	2.4	615
	180	2.1	692
	200	1.9	769

-----  
DISCOUNTED CASH FLOW ANALYSIS  
-----

REQUIRED ASSUMPTIONS	AMOUNT
Marginal Tax Rate (%)	34.00%
Discount Rate (%)	21.00%

CASH FLOW - 5 YEAR PROPERTY	SYSTEM COST	YEAR (-	1	2	3	4	5	6	CASH FLOW TOTALS
MACRS DEPRECIATION METHOD									
RECURRING OPERATION SAVINGS	-2054600		735833	735833	735833	735833	735833	735833	4415000
LESS: INCOME TAX EFFECTS			250183	250183	250183	250183	250183	250183	1501100
NET CASH FLOW FROM OPERATION SAVINGS	-2054600		485650	485650	485650	485650	485650	485650	2913900
=====									
RDSS SYSTEM COST			2054600	2054600	2054600	2054600	2054600	2054600	N/A
MACRS DEPRECIATION (%)			20.000%	32.000%	19.200%	11.520%	11.520%	5.760%	N/A
TAX EFFECTS OF MACRS DEPRECIATION	-2054600		410920	657472	394483	236690	236690	118345	2054600
PLUS: NET CASH FLOW FROM OPERATIONS SAVINGS			485650	485650	485650	485650	485650	485650	2913900
NET INCREASE (DECREASE) IN CASH FLOW	-2054600		896570	1143122	888133	722340	722340	603995	4968500
=====									

OPTIONAL STRAIGHT LINE METHOD									
RDSS SYSTEM COST			2054600	2054600	2054600	2054600	2054600	2054600	N/A
OPTIONAL STRAIGHT LINE DEPREC. (%)			10.000%	20.000%	20.000%	20.000%	20.000%	10.000%	N/A
TAX EFFECTS OF OPTIONAL S. L.	-2054600		205460	410920	410920	410920	410920	205460	2054600
PLUS: NET CASH FLOW FROM OPERATIONS			485650	485650	485650	485650	485650	485650	2913900
NET INCREASE (DECREASE) IN CASH FLOW	-2054600		691110	896570	896570	896570	896570	691110	4968500
=====									

CASH FLOW - 7 YEAR PROPERTY		SYSTEM	YEAR						
		COST	1	2	3	4	5	6	7
MACRS DEPRECIATION METHOD									
RECURRING OPERATION SAVINGS	-2054600	735833	735833	735833	735833	735833	735833	735833	735833
LESS: INCOME TAX EFFECTS		250183	250183	250183	250183	250183	250183	250183	250183
NET CASH FLOW FROM OPERATION SAVINGS	-2054600	485650	485650	485650	485650	485650	485650	485650	485650
RDSS SYSTEM COST									
		2054600	2054600	2054600	2054600	2054600	2054600	2054600	2054600
MACRS DEPRECIATION (%)									
		14.290%	24.490%	17.490%	12.490%	8.930%	8.930%	8.930%	4.450%
TAX EFFECTS OF MACRS DEPRECIATION	-2054600	293602	503172	359350	256620	183476	183476	183476	91430
PLUS: NET CASH FLOW FROM OPERATIONS SAVINGS		485650	485650	485650	485650	485650	485650	485650	485650
NET INCREASE (DECREASE) IN CASH FLOW	-2054600	779252	988822	845000	742270	669126	669126	669126	577080
OPTIONAL STRAIGHT LINE METHOD									
RDSS SYSTEM COST									
		2054600	2054600	2054600	2054600	2054600	2054600	2054600	2054600
OPTIONAL STRAIGHT LINE TAX RATE									
		7.130%	14.290%	14.290%	14.290%	14.290%	14.290%	14.290%	7.130%
TAX EFFECTS OF OPTIONAL S. L.	-2054600	146493	293602	293602	293602	293602	293602	293602	146493
PLUS: NET CASH FLOW FROM OPERATIONS		485650	485650	485650	485650	485650	485650	485650	485650
NET INCREASE (DECREASE) IN CASH FLOW	-2054600	632143	779252	779252	779252	779252	779252	779252	632143

PRESENT VALUE SUMMARY

	MACRS 5 YEAR DEPRECIATION	S. L. 5 YEAR DEPRECIATION	MACRS 7 YEAR DEPRECIATION	S. L. 7 Y DEPRECIAT
RECURRING OPERATIONS SAVINGS	2387496	2387496	2741403	2741403
LESS: INCOME TAX EFFECTS	811749	811749	932077	932077
NET CASH FLOW FROM OPERATIONS SAVINGS	1575747	1575747	1809326	1809326
PLUS: TAX EFFECTS OF DEPRECIATION	1250721	1098010	1106289	940244
TOTAL NET PRESENT VALUE OF CASH FLOWS	2826469	2673757	2915615	2749570
LESS: PROCUREMENT AND INSTALLATION	2054600	2054600	2054600	2054600
NET PRESENT VALUE	771869	619157	861015	694970
NET PRESENT VALUE PER INSTALLED UNIT	\$1,731	\$1,388	\$1,931	\$1,558

# ----- NPV SENSITIVITY ANALYSIS -----

	AMOUNT	HACRS 5 YEAR DEPRECIATION	S. L. 5 YEAR DEPRECIATION	HACRS 7 YEAR DEPRECIATION	S. L. 7 Y DEPRECIAT
MONTHLY CASH FLOW GAIN (LOSS) PER UNIT AFTER ALL EXPENSES:					
	(\$40)	(\$2,830)	(\$3,173)	(\$3,307)	(\$3,679)
	(20)	(2,316)	(2,659)	(2,716)	(3,089)
	0	(1,802)	(2,145)	(2,126)	(2,499)
	20	(1,288)	(1,631)	(1,536)	(1,908)
	40	(775)	(1,117)	(946)	(1,318)
	60	(261)	(603)	(374)	(728)
	80	253	(89)	234	(138)
	100	767	425	824	452
	120	1,281	939	1,415	1,042
	140	1,795	1,453	2,005	1,632
	160	2,309	1,967	2,595	2,222
	180	2,823	2,481	3,185	2,813
	200	\$3,337	\$2,995	\$3,775	\$3,403

## ----- INTERNAL RATE OF RETURN ESTIMATES -----

Note: A guess of the Internal Rate of Return is required to run this module. The guess is entered as a decimal and converted by the program to a percent figure. An "ERR" response is displayed if the spread sheet can not reach an IRR. In this case you should try a different guess.

IRR ESTIMATE	15.00%				
		HACRS 5 YEAR DEPRECIATION	S. L. 5 YEAR DEPRECIATION	HACRS 7 YEAR DEPRECIATION	S. L. 7 Y DEPRECIAT
RECURRING OPERATIONS SAVINGS		27%	27%	32%	32%
AFTER TAX NET CASH FLOW FROM OPERATIONS SAVINGS		11%	11%	17%	17%
NET INCREASE (DECREASE) IN CASH FLOW		37%	33%	36%	32%

# IRR SENSITIVITY ANALYSIS

	AMOUNT	MACRS 5 YEAR DEPRECIATION	S. L. 5 YEAR DEPRECIATION	MACRS 7 YEAR DEPRECIATION	S. L. 7 Y DEPRECIAT
MONTHLY CASH FLOW GAIN (LOSS) PER UNIT AFTER ALL EXPENSES:	\$0	-0%	-0%	0%	-0%
	20	7%	6%	7%	6%
	40	14%	11%	13%	11%
	60	18%	16%	19%	16%
	80	23%	20%	24%	20%
	100	29%	25%	28%	24%
	120	33%	29%	32%	28%
	140	37%	33%	36%	32%
	160	42%	37%	40%	36%
	180	46%	41%	44%	40%
	200	50%	45%	48%	44%
				37708.00	

## REVENUE AND COST INFORMATION

	REQUIRED	COMPUTED
Average number of linehaul units in use per month		446.0
Average revenue per mile		\$1.580
Average variable operating expenses per mile		\$1.320
Average contribution		\$0.260

# REVENUE INCREASES

## Premium service:

Existing premium service revenues per month	\$0
Projected improvement with the satellite system (%)	0%
Sales and marketing expense ratio (%)	0%
Current premium service costs per month	\$0
Projected increase in premium service costs (%)	0%
Increase in Marketing revenues per month	\$0
Applied sales and marketing expense ratio	\$0
Projected cost increase per month	\$0
Contribution per linehaul unit per month	\$0.00

## Miscellaneous

Total miscellaneous contribution increase per month	\$0
Miscellaneous contribution per line haul unit per month	\$0.00

# EXPENSE REDUCTION MODULE

## Deadhead reduction:

## REQUIRED COMPUTED

Average number of miles per month per linehaul unit	5,952
Average loaded miles (%)	85%
Average loaded miles	5,059
Estimated increase in loaded miles (%)	10%
Estimated loaded miles per month	5,565
Estimated increase in contribution per month	\$131.54

Driver and equipment productivity:	REQUIRED	COMPUTED
Average number of linehaul drivers per month	446.0	
Average on-duty driving hours per month	166.0	
Average on-duty NON-driving hours per month	0.0	
Projected improvement with satellite system in hours per month	17.0	
Average speed in MPH	40.0	
Average miles per driver per month	6,720	
Increase in total miles per month per driver at average speed	680	
Increase in loaded miles per driver per month	646	
Improvement in revenue per driver per month	\$1,021	
Variable expense per driver per month impact	\$898	
Increase in contribution per driver per month	\$123	
Increase in contribution per linehaul unit per month	\$123.08	
Layover pay:	REQUIRED	COMPUTED
Total layover pay per month	\$0.00	
Estimated average reduction (%)	0%	
Projected layover expense reduction	\$0.00	
Average number of linehaul units per month	446.0	
Reduction in average layover expense per linehaul unit	\$0.00	
Dispatcher productivity:	REQUIRED	COMPUTED
Existing dispatcher hours per month	0.0	
Projected reduction with satellite system (%)	0%	
Average dispatcher wages and fringes per hour	\$0.00	
Projected impact in hours per month	0.0	
Projected monthly reduction in labor costs	\$0.00	
Average number of linehaul units per month	446.0	
Reduction of dispatcher wages and fringes per linehaul unit per month	\$0.00	



Security, Safety, and Insurance:

REQUIRED COMPUTED

Total insurance premium expense per month	\$0
Estimated premium reduction (%)	0%
Projected premium savings per month	\$0.00
Total claims expense per month	\$0
Estimated claims reduction (%)	0%
Projected claims savings per month	\$0.00
Total insurance premium and claims savings per month	\$0.00
Insurance and claims expense reduction per linehaul unit per month	\$0.00

Administrative expenses:

REQUIRED COMPUTED

Existing administrative expenses per month	\$0.00
Projected improvement with satellite system (%)	0%
Estimated monthly administrative expense reduction	\$0.00
Estimated monthly admin expense reduction per linehaul unit per month	\$0.00

Telecommunications expense:

REQUIRED COMPUTED

Existing telephone expense per linehaul unit per month	\$64.66
Projected reduction with satellite system (%)	60.00%
Estimated reduction per month	\$38.80

Miscellaneous:

Estimated reduction in miscellaneous expenses	\$0.00
Estimated reduction per linehaul unit per month	\$0.00

# COST INCREASES MODULE

Monthly charges for the satellite service:	REQUIRED	COMPUTED
Monthly charge per installed unit	\$150.00	
Equipment lease expenses per unit (if required)	\$0.00	
Nationwide pager service per unit (if required)	\$0.00	
Total	\$150.00	
Telecommunications expenses:	REQUIRED	COMPUTED
Total estimated costs for communication with the network management center	\$785.40	
Estimated costs per linehaul unit	\$1.76	
Maintenance expense PER YEAR:	REQUIRED	COMPUTED
Office equipment	\$0.00	
Software updates	\$0.00	
Per linehaul unit	\$50.00	
Cost per linehaul unit per month	\$4.17	
Miscellaneous		
Total miscellaneous cost increases per month	\$0	
Miscellaneous cost increases per linehaul unit per month	\$0.00	

# PAYBACK PERIOD SENSITIVITY PER INSTALLED UNIT

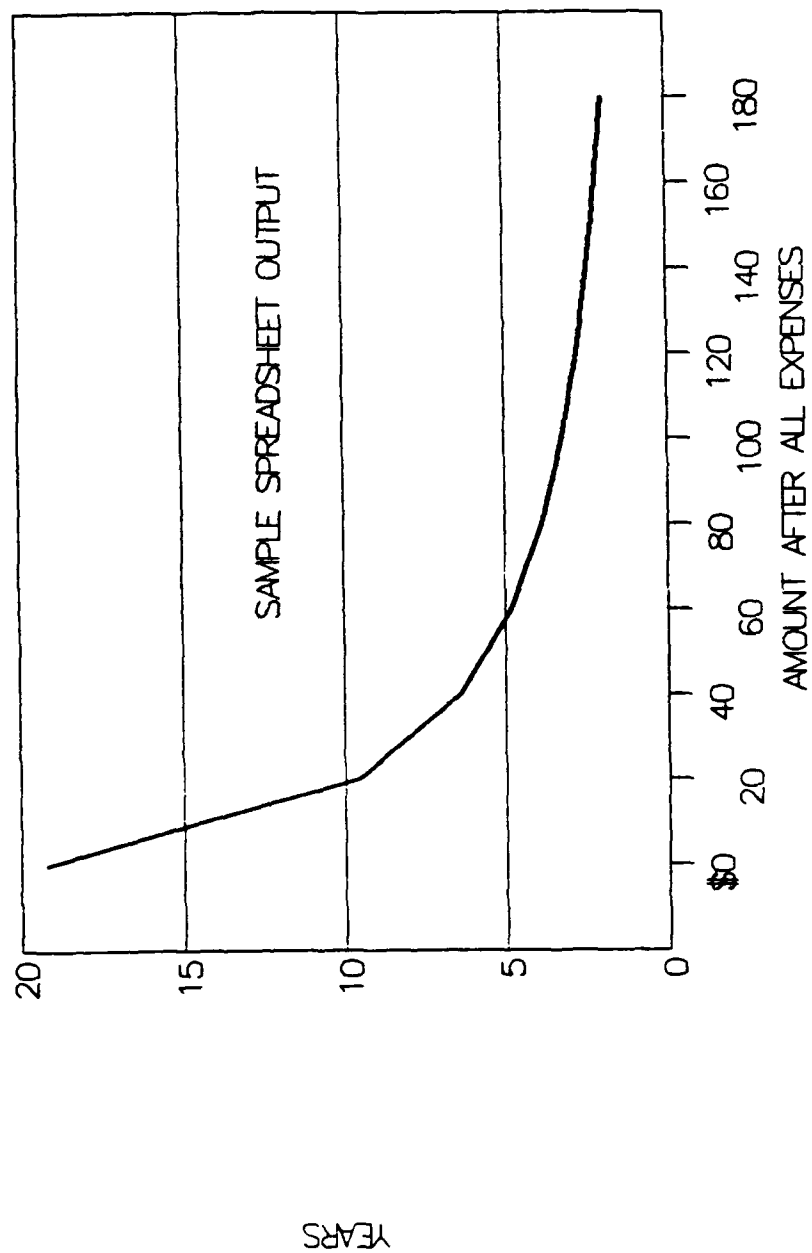


Figure 165. Payback Period Sensitivity Per Installed Unit

# NET PRESENT VALUE SENSITIVITY PER INSTALLED UNIT

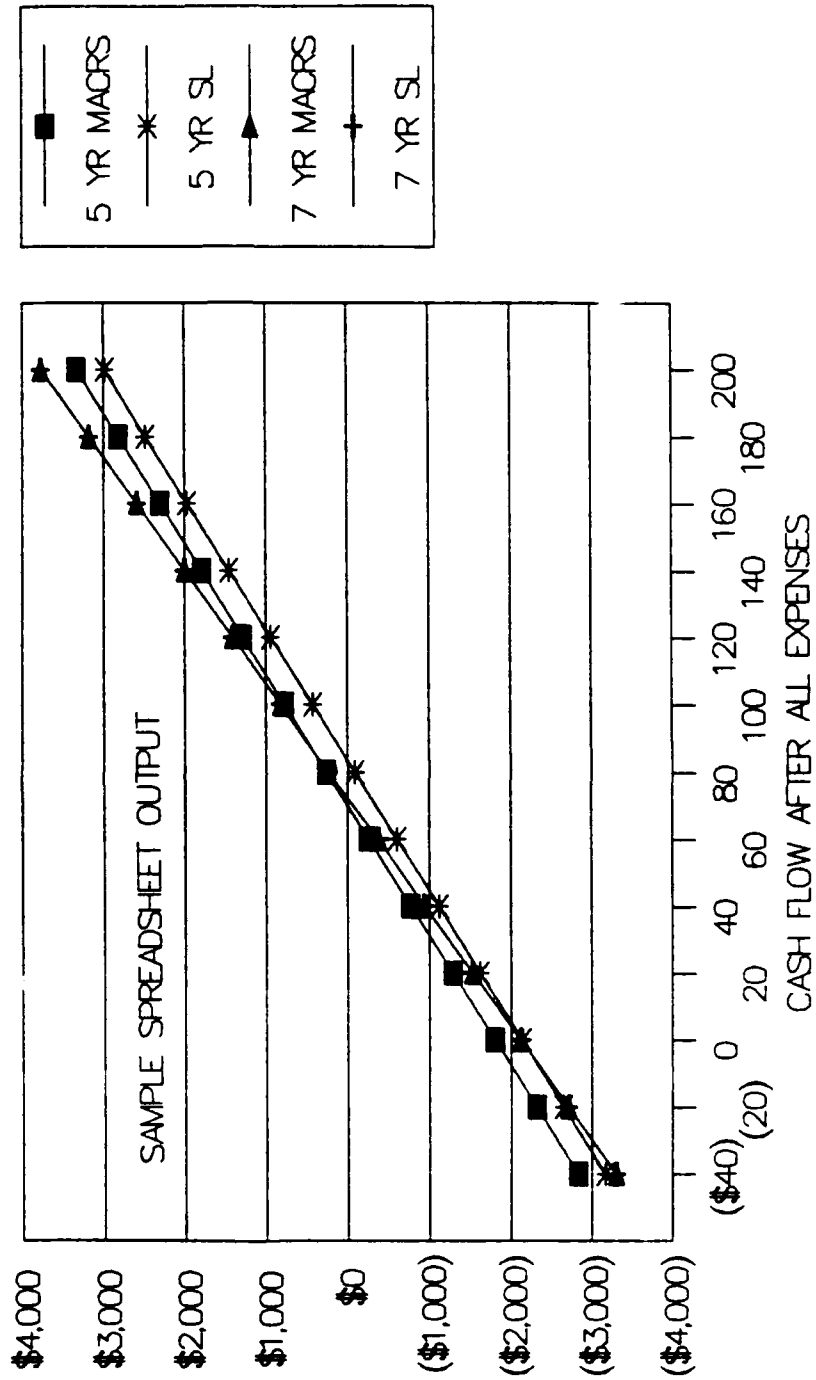


Figure 166. Net Present Value Sensitivity  
Per Installed Unit

# IRR SENSITIVITY PER INSTALLED UNIT

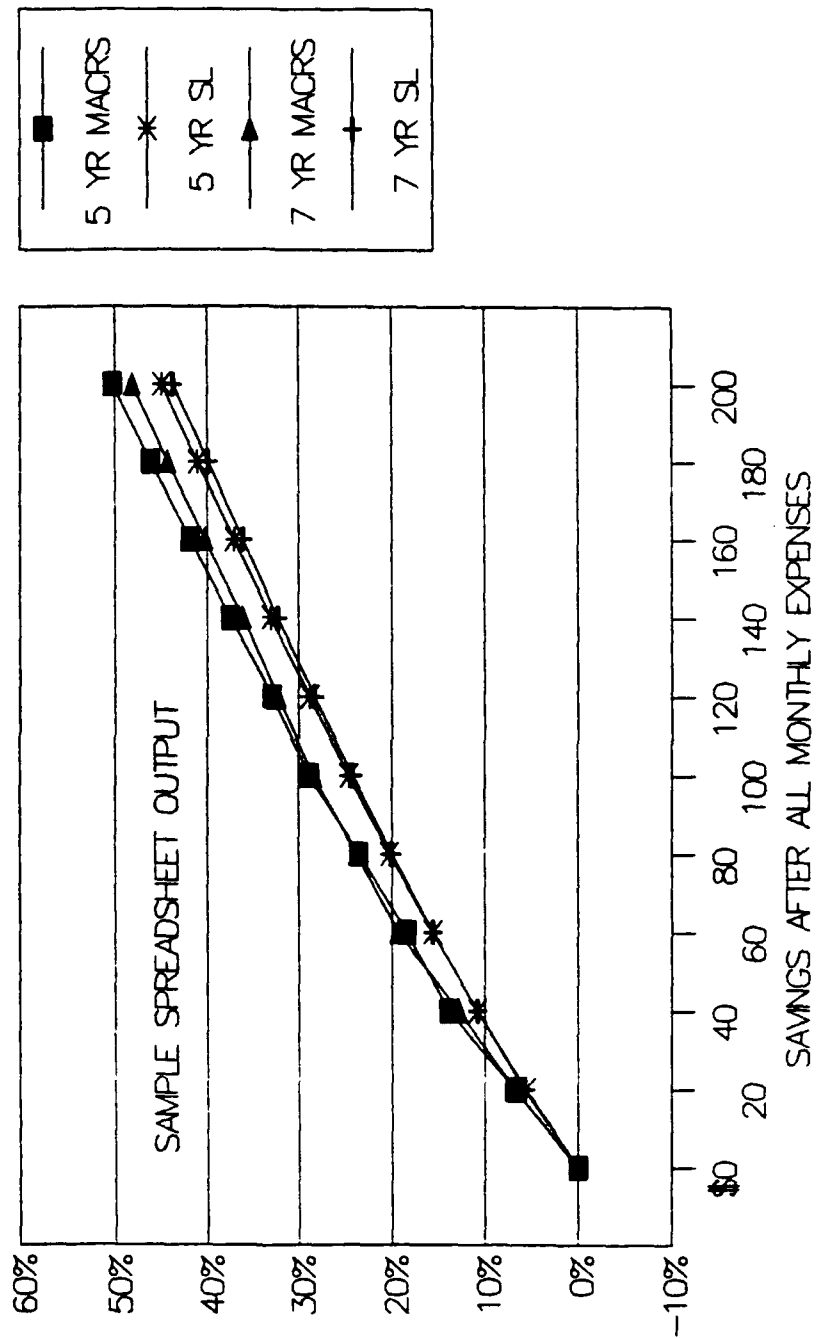


Figure 167. IRR Sensitivity Per Installed Unit



B32: (C2) [W9] +L375  
 C33: [W5] 'Driver productivity  
 B33: (,2) [W9] +L399  
 C34: [W5] 'Layover Pay  
 B34: (,2) [W9] +L413  
 C35: [W5] 'Dispatcher productivity  
 B35: (,2) [W9] +L430  
 C36: [W5] 'Security, Safety, Insurance  
 B36: (,2) [W9] +L449  
 C37: [W5] 'Administrative expenses  
 B37: (,2) [W9] +L460  
 C38: [W5] 'Miscellaneous  
 B38: (,2) [W9] +L474  
 B40: [W9] 'Telecommunications  
 B41: [W9] 'Expenses:  
 C42: [W5] 'Reduction of expenditures  
 B42: (C2) [W9] +L458  
 C43: [W5] 'Miscellaneous  
 B43: (,2) [W9] +L474  
 B44: [W9] '-----  
 B45: [W9] 'Subtotal:  
 C45: [W5] 'Gross increases  
 I45: (C2) [W11] @SUM(B27..B43)  
 B47: [W9] 'Less:  
 C48: [W5] 'Monthly service charge  
 B48: (C2) [W9] +K482  
 C49: [W5] 'Equipment lease expenses  
 B49: (,2) [W9] +K484  
 C50: [W5] 'Nationwide pager service (if used)  
 B50: (,2) [W9] +K486  
 C51: [W5] 'Monthly charge for communication  
 C52: [W5] ' with the network management center  
 B52: (,2) [W9] +L495  
 C53: [W5] 'Maintenance  
 B53: (,2) [W9] +L505  
 C54: [W5] 'Miscellaneous  
 B54: (,2) [W9] +L511  
 B55: [W9] '-----  
 B56: [W9] 'Total Expenses  
 I56: (,2) [W11] @SUM(B48..B54)  
 I57: [W11] '-----  
 C58: [W5] 'Gain / (Loss) per unit per month  
 I58: (C2) [W11] +I45-I56  
 I59: [W11] '-----  
 B61: [W9]

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D62: [W9] 'CASH FLOW AND PRESENT VALUE MODULE  
 B64: [W9] 'Note: This module performs a discounted cash flow analysis and  
 B65: [W9] ' includes income tax and depreciation effects. Depreciation  
 B66: [W9] ' is figured under both the 5 and 7 year MACRS schedule and the  
 B67: [W9] ' alternate straight line method in accordance with IRS pub  
 B68: [W9] ' 534 (Rev. Dec. 87).  
 B72: [W9] '-----  
 G72: [W9] '-----  
 I72: [W11] '-----  
 D73: [W9] 'TOTAL  
 G73: [W9] 'REQUIRED  
 I73: [W11] 'COMPUTED  
 C74: [W5] 'CAPITAL OUTLAYS  
 G74: [W9] 'INFORMATION  
 I74: [W11] 'TOTALS  
 B75: [W9] '-----  
 G75: [W9] '-----  
 I75: [W11] '-----  
 C76: [W5] 'REQUIRED INFORMATION  
 B77: [W9] 'Number of units installed  
 G77: (F0) [W9] 446  
 I77: (F0) [W11] +G77  
 B79: [W9] 'Cost of equipment per unit  
 G79: (C0) [W9] 4500  
 I79: (C0) [W11] +I77\*G79  
 B80: [W9] 'Cost of installation per unit  
 G80: (,0) [W9] 100  
 I80: (,0) [W11] +I77\*G80  
 B81: [W9] 'Cost of software package  
 G81: (,0) [W9] 3000  
 I81: (,0) [W11] +G81  
 B82: [W9] 'Cost of additional ADP/MIS  
 B83: [W9] ' equipment  
 I83: (,0) [W11] +G83  
 B84: [W9] 'Miscellaneous  
 G84: (,0) [W9] 0  
 I84: (,0) [W11] +G84  
 I85: (F0) [W11] '-----  
 B86: [W9] ' SYSTEM TOTAL COST  
 I86: (C0) [W11] @SUM(I79..I84)  
 I87: (C0) [W11] '-----  
 B89: [W9] 'Total system cost per unit  
 I89: (C0) [W11] +I86/G77  
 B91: [W9] '-----  
 I91: [W11] '-----  
 B92: [W9] 'PAYBACK PERIOD ANALYSIS

I92: [W11] 'COMPUTED	H118: (,0) [W9] +F118/L324
B93: [W9] '-----	F119: (,0) 180
I93: [W11] '-----	I119: (,1) [W11] +I89/F119/12
B95: [W9] 'System Total Cost	H119: (,0) [W9] +F119/L324
I95: (C0) [W11] +I86	F120: (,0) 200
B97: [W9] 'Total Gain (Loss) per Month	I120: (,1) [W11] +I89/F120/12
I97: (C0) [W11] +I58*G77	H120: (,0) [W9] +F120/L324
B99: [W9] 'Payback Period in Months	B123: [W9] '-----
I99: (F1) [W11] +I95/I97	B124: [W9] 'DISCOUNTED CASH FLOW ANALYSIS
B101: [W9] 'Payback Period in Years	B125: [W9] '-----
I101: (F1) [W11] +I99/12	B128: [W9] '-----
B103: '----- [W9]	G128: [W9] '-----
B104: [W9] 'PAYBACK PERIOD SENSITIVITY	B129: [W9] 'REQUIRED ASSUMPTIONS
ANALYSIS	G129: [W9] 'AMOUNT
B105: '----- [W9]	B130: [W9] '-----
	G130: [W9] '-----
I107: [W11] 'PAYBACK PERIOD	B131: [W9] 'Marginal Tax Rate (%)
L107: [W9] 'EQUIVALENT ADDITIONAL	G131: (P2) [W9] 0.34
F108: 'AMOUNT	B132: [W9] 'Discount Rate (%)
I108: [W11] 'IN YEARS	G132: (P2) [W9] 0.21
L108: [W9] 'LOADED MILES	B134: [W9] '-----
B110: [W9] 'MONTHLY CASH FLOW GAIN	B135: [W9] 'CASH FLOW - 5 YEAR PROPERTY
F110: (C0) 0	G135: [W9] 'SYSTEM
I110: [W11] 'N/A	H135: [W9] 'YEAR <-----
H110: (,0) [W9] 0	I135: [W11] '-----
B111: [W9] 'PER UNIT AFTER ALL EXPENSES:	J135: [W9] '-----
F111: (,0) 20	K135: [W9] '-----
I111: (,1) [W11] +I89/F111/12	L135: [W9] '-----
H111: (,0) [W9] +F111/L324	H135: [W9] '-----
F112: (,0) 40	H135: [W9] 'CASH
I112: (,1) [W11] +I89/F112/12	B136: [W9] '-----
H112: (,0) [W9] +F112/L324	G136: (F0) [W9] 'COST
F113: (,0) 60	H136: [W9] 'FLOW TOTALS
I113: (,1) [W11] +I89/F113/12	H137: (F0) [W9] '1
H113: (,0) [W9] +F113/L324	I137: (F0) [W11] '2
F114: (,0) 80	J137: (F0) [W9] '3
I114: (,1) [W11] +I89/F114/12	K137: (F0) [W9] '4
H114: (,0) [W9] +F114/L324	L137: (F0) [W9] '5
F115: (,0) 100	H137: (F0) [W9] '6
I115: (,1) [W11] +I89/F115/12	G138: [W5] 'MACRS DEPRECIATION METHOD
H115: (,0) [W9] +F115/L324	B140: [W9] 'RECURRING OPERATION SAVINGS
F116: (,0) 120	G140: (G) [W9] -I86
I116: (,1) [W11] +I89/F116/12	H140: (F0) [W9] +I58*12*G77
H116: (,0) [W9] +F116/L324	I140: (F0) [W11] +I58*12*G77
F117: (,0) 140	J140: (F0) [W9] +I58*12*G77
I117: (,1) [W11] +I89/F117/12	K140: (F0) [W9] +I58*12*G77
H117: (,0) [W9] +F117/L324	L140: (F0) [W9] +I58*12*G77
F118: (,0) 160	H140: (F0) [W9] +I58*12*G77
I118: (,1) [W11] +I89/F118/12	H140: (F0) [W9] 8508(H140..H140)
	B142: [W9] 'LESS: INCOME TAX EFFECTS



H142: (FO) [W9] +H140\*G131  
 I142: (FO) [W11] +H140\*G131  
 J142: (FO) [W9] +H140\*G131  
 K142: (FO) [W9] +H140\*G131  
 L142: (FO) [W9] +H140\*G131  
 H142: (FO) [W9] +H140\*G131  
 H142: (FO) [W9] @SUM(H142..H142)  
 H143: (FO) [W9] '-----  
 I143: (FO) [W11] '-----  
 J143: (FO) [W9] '-----  
 K143: (FO) [W9] '-----  
 L143: (FO) [W9] '-----  
 H143: (FO) [W9] '-----  
 H143: (FO) [W9] '-----  
 B144: [W9] 'NET CASH FLOW FROM OPERATION  
 SAVINGS  
 G144: (FO) [W9] -I86  
 H144: (FO) [W9] +H140-H142  
 I144: (FO) [W11] +I140-I142  
 J144: (FO) [W9] +J140-J142  
 K144: (FO) [W9] +K140-K142  
 L144: (FO) [W9] +L140-L142  
 H144: (FO) [W9] +H140-H142  
 H144: (FO) [W9] @SUM(H144..H144)  
 H145: [W9] '-----  
 I145: [W11] '-----  
 J145: [W9] '-----  
 K145: [W9] '-----  
 L145: [W9] '-----  
 H145: [W9] '-----  
 H145: [W9] '-----  
 B147: [W9] ' RDSS SYSTEM COST  
 H147: (FO) [W9] +I86  
 I147: (FO) [W11] +I86  
 J147: (FO) [W9] +I86  
 K147: (FO) [W9] +I86  
 L147: (FO) [W9] +I86  
 H147: (FO) [W9] +I86  
 H147: [W9] 'N/A  
 B149: [W9] ' MACRS DEPRECIATION (%)  
 H149: (P3) [W9] 0.2  
 I149: (P3) [W11] 0.32  
 J149: (P3) [W9] 0.192  
 K149: (P3) [W9] 0.1152  
 L149: (P3) [W9] 0.1152  
 H149: (P3) [W9] 0.0576  
 H149: (P4) [W9] 'N/A  
 H150: (FO) [W9] '-----  
 I150: (FO) [W11] '-----  
 J150: (FO) [W9] '-----

K150: (FO) [W9] '-----  
 L150: (FO) [W9] '-----  
 H150: (FO) [W9] '-----  
 B151: [W9] ' TAX EFFECTS OF MACRS  
 DEPRECIATION  
 G151: (FO) [W9] -I86  
 H151: (FO) [W9] +H149\*I86  
 I151: (FO) [W11] +I149\*I86  
 J151: (FO) [W9] +J149\*I86  
 K151: (FO) [W9] +K149\*I86  
 L151: (FO) [W9] +L149\*I86  
 H151: (FO) [W9] +H149\*I86  
 H151: (FO) [W9] @SUM(H151..H151)  
 B153: [W9] ' PLUS: NET CASH FLOW FROM  
 OPERATIONS SAVINGS  
 H153: (FO) [W9] +H144  
 I153: (FO) [W11] +I144  
 J153: (FO) [W9] +J144  
 K153: (FO) [W9] +K144  
 L153: (FO) [W9] +L144  
 H153: (FO) [W9] +H144  
 H153: (FO) [W9] @SUM(H153..H153)  
 H154: (FO) [W9] '-----  
 I154: (FO) [W11] '-----  
 J154: (FO) [W9] '-----  
 K154: (FO) [W9] '-----  
 L154: (FO) [W9] '-----  
 H154: (FO) [W9] '-----  
 H154: (FO) [W9] '-----  
 B155: [W9] 'NET INCREASE (DECREASE) IN CASH  
 FLOW  
 G155: (FO) [W9] -I86  
 H155: (FO) [W9] +H151+H153  
 I155: (FO) [W11] +I151+I153  
 J155: (FO) [W9] +J151+J153  
 K155: (FO) [W9] +K151+K153  
 L155: (FO) [W9] +L151+L153  
 H155: (FO) [W9] +H151+H153  
 H155: (FO) [W9] @SUM(H155..H155)  
 H156: (FO) [W9] '-----  
 I156: (FO) [W11] '-----  
 J156: (FO) [W9] '-----  
 K156: (FO) [W9] '-----  
 L156: (FO) [W9] '-----  
 H156: (FO) [W9] '-----  
 H156: (FO) [W9] '-----  
 C160: [W5] 'OPTIONAL STRAIGHT LINE METHOD  
 B162: [W9] ' RDSS SYSTEM COST  
 H162: (FO) [W9] +I86  
 I162: (FO) [W11] +I86

J162: (P0) [W9] +I86	I170: (P0) [W11] +I168+I166
K162: (P0) [W9] +I86	J170: (P0) [W9] +J168+J166
L162: (P0) [W9] +I86	K170: (P0) [W9] +K168+K166
M162: (P0) [W9] +I86	L170: (P0) [W9] +L168+L166
N162: (P0) [W9] "N/A	M170: (P0) [W9] +M168+M166
B164: [W9] "OPTIONAL STRAIGHT LINE	N170: (P0) [W9] @SUM(H170..H170)
DEPRNC. (X)	H171: (P0) [W9] "-----
H164: (P3) [W9] 0.1	I171: (P0) [W11] "-----
I164: (P3) [W11] 0.2	J171: (P0) [W9] "-----
J164: (P3) [W9] 0.2	K171: (P0) [W9] "-----
K164: (P3) [W9] 0.2	L171: (P0) [W9] "-----
L164: (P3) [W9] 0.2	M171: (P0) [W9] "-----
M164: (P3) [W9] 0.1	N171: (P0) [W9] "-----
N164: (P4) [W9] "N/A	B173: [W9] "-----
H165: (P0) [W9] "-----	B174: [W9] "CASH FLOW - 7 YEAR PROPERTY
I165: (P0) [W11] "-----	G174: (P0) [W9] "SYSTEM
J165: (P0) [W9] "-----	H174: [W9] "YEAR <-----
K165: (P0) [W9] "-----	I174: [W11] "-----
L165: (P0) [W9] "-----	J174: [W9] "-----
M165: (P0) [W9] "-----	K174: [W9] "-----
B166: [W9] "TAX EFFECTS OF OPTIONAL S. L.	L174: [W9] "-----
	H174: [W9] "-----
	N174: [W9] "-----
	O174: [W9] "-----
G166: (P0) [W9] -I86	P174: [W11] "CASH
H166: (P0) [W9] +H164+H162	B175: [W9] "-----
I166: (P0) [W11] +I164+I162	G175: (P0) [W9] "COST
J166: (P0) [W9] +J164+J162	P175: [W11] "FLOW TOTALS
K166: (P0) [W9] +K164+K162	H176: (P0) [W9] "1
L166: (P0) [W9] +L164+L162	I176: (P0) [W11] "2
M166: (P0) [W9] +M164+M162	J176: (P0) [W9] "3
N166: (P0) [W9] @SUM(H166..H166)	K176: (P0) [W9] "4
B168: [W9] "PLUS: NET CASH FLOW FROM	L176: (P0) [W9] "5
OPERATIONS	M176: (P0) [W9] "6
H168: (P0) [W9] +H144	N176: (P0) [W9] "7
I168: (P0) [W11] +I144	O176: [W9] "8
J168: (P0) [W9] +J144	C177: [W5] "MACRS DEPRECIATION METHOD
K168: (P0) [W9] +K144	B179: [W9] "RECURRING OPERATION SAVINGS
L168: (P0) [W9] +L144	G179: (P0) [W9] -I86
M168: (P0) [W9] +M144	H179: (P0) [W9] +I58*12*G77
N168: (P0) [W9] @SUM(H168..H168)	I179: (P0) [W11] +I58*12*G77
H169: (P0) [W9] "-----	J179: (P0) [W9] +I58*12*G77
I169: (P0) [W11] "-----	K179: (P0) [W9] +I58*12*G77
J169: (P0) [W9] "-----	L179: (P0) [W9] +I58*12*G77
K169: (P0) [W9] "-----	M179: (P0) [W9] +I58*12*G77
L169: (P0) [W9] "-----	N179: (P0) [W9] +I58*12*G77
M169: (P0) [W9] "-----	O179: (P0) [W9] +I58*12*G77
N169: (P0) [W9] "-----	P179: (P0) [W11] @SUM(H179..O179)
B170: [W9] "NET INCREASE (DECREASE) IN CASH	B181: [W9] "LESS: INCOME TAX EFFECTS
FLOW	H181: (P0) [W9] +G131+H179
G170: (P0) [W9] -I86	
H170: (P0) [W9] +H168+H166	

I181: (FO) [W11] +G131*I179	I188: (P3) [W11] 0.2449
J181: (FO) [W9] +G131*J179	J188: (P3) [W9] 0.1749
K181: (FO) [W9] +G131*K179	K188: (P3) [W9] 0.1249
L181: (FO) [W9] +G131*L179	L188: (P3) [W9] 0.0893
M181: (FO) [W9] +G131*M179	M188: (P3) [W9] 0.0893
N181: (FO) [W9] +G131*N179	N188: (P3) [W9] 0.0893
O181: (FO) [W9] +G131*O179	O188: (P3) [W9] 0.0445
P181: (FO) [W11] @SUM(H181..O181)	P188: (F4) [W11] "N/A
H182: (FO) [W9] "-----	H189: (FO) [W9] "-----
I182: (FO) [W11] "-----	I189: (FO) [W11] "-----
J182: (FO) [W9] "-----	J189: (FO) [W9] "-----
K182: (FO) [W9] "-----	K189: (FO) [W9] "-----
L182: (FO) [W9] "-----	L189: (FO) [W9] "-----
M182: (FO) [W9] "-----	M189: (FO) [W9] "-----
N182: (FO) [W9] "-----	N189: (FO) [W9] "-----
O182: (FO) [W9] "-----	O189: (FO) [W9] "-----
P182: (FO) [W11] "-----	B190: [W9] "TAX EFFECTS OF MACRS
B183: [W9] "NET CASH FLOW FROM OPERATION	DEPRECIATION
SAVINGS	G190: (FO) [W9] -I86
G183: (FO) [W9] -I86	H190: (FO) [W9] +H188*H186
H183: (FO) [W9] +H179-H181	I190: (FO) [W11] +I188*I186
I183: (FO) [W11] +I179-I181	J190: (FO) [W9] +J188*J186
J183: (FO) [W9] +J179-J181	K190: (FO) [W9] +K188*K186
K183: (FO) [W9] +K179-K181	L190: (FO) [W9] +L188*L186
L183: (FO) [W9] +L179-L181	M190: (FO) [W9] +M188*M186
M183: (FO) [W9] +M179-M181	N190: (FO) [W9] +N188*N186
N183: (FO) [W9] +N179-N181	O190: (FO) [W9] +O188*O186
O183: (FO) [W9] +O179-O181	P190: (FO) [W11] @SUM(H190..O190)
P183: (FO) [W11] @SUM(H183..O183)	B192: [W9] "PLUS: NET CASH FLOW FROM
H184: (FO) [W9] "-----	OPERATIONS SAVINGS
I184: (FO) [W11] "-----	H192: (FO) [W9] +H183
J184: (FO) [W9] "-----	I192: (FO) [W11] +I183
K184: (FO) [W9] "-----	J192: (FO) [W9] +J183
L184: (FO) [W9] "-----	K192: (FO) [W9] +K183
M184: (FO) [W9] "-----	L192: (FO) [W9] +L183
N184: (FO) [W9] "-----	M192: (FO) [W9] +M183
O184: (FO) [W9] "-----	N192: (FO) [W9] +N183
P184: (FO) [W11] "-----	O192: (FO) [W9] +O183
B186: [W9] "RDSS SYSTEM COST	P192: (FO) [W11] @SUM(H192..O192)
H186: (FO) [W9] +I86	H193: (FO) [W9] "-----
I186: (FO) [W11] +I86	I193: (FO) [W11] "-----
J186: (FO) [W9] +I86	J193: (FO) [W9] "-----
K186: (FO) [W9] +I86	K193: (FO) [W9] "-----
L186: (FO) [W9] +I86	L193: (FO) [W9] "-----
M186: (FO) [W9] +I86	M193: (FO) [W9] "-----
N186: (FO) [W9] +I86	N193: (FO) [W9] "-----
O186: (FO) [W9] +I86	O193: (FO) [W9] "-----
P186: (FO) [W11] "N/A	P193: (FO) [W11] "-----
B188: [W9] "MACRS DEPRECIATION (X)	B194: [W9] "NET INCREASE (DECREASE) IN CASH
H188: (P3) [W9] 0.1429	FLOW

G194: (FO) [W9] -I86  
 H194: (FO) [W9] +H190+H192  
 I194: (FO) [W11] +I190+I192  
 J194: (FO) [W9] +J190+J192  
 K194: (FO) [W9] +K190+K192  
 L194: (FO) [W9] +L190+L192  
 M194: (FO) [W9] +M190+M192  
 N194: (FO) [W9] +N190+N192  
 O194: (FO) [W9] +O190+O192  
 P194: (FO) [W11] @SUM(H194..O194)  
 H195: (FO) [W9] '-----  
 I195: (FO) [W11] '-----  
 J195: (FO) [W9] '-----  
 K195: (FO) [W9] '-----  
 L195: (FO) [W9] '-----  
 M195: (FO) [W9] '-----  
 N195: (FO) [W9] '-----  
 O195: (FO) [W9] '-----  
 P195: (FO) [W11] '-----  
 C197: [W5] 'OPTIONAL STRAIGHT LINE METHOD  
 B199: [W9] ' RDSS SYSTEM COST  
 H199: (FO) [W9] +I86  
 I199: (FO) [W11] +I86  
 J199: (FO) [W9] +I86  
 K199: (FO) [W9] +I86  
 L199: (FO) [W9] +I86  
 M199: (FO) [W9] +I86  
 N199: (FO) [W9] +I86  
 O199: (FO) [W9] +I86  
 P199: (FO) [W11] 'N/A  
 B201: [W9] ' OPTIONAL STRAIGHT LINE TAX  
 RATE  
 H201: (P3) [W9] 0.0713  
 I201: (P3) [W11] 0.1429  
 J201: (P3) [W9] 0.1429  
 K201: (P3) [W9] 0.1429  
 L201: (P3) [W9] 0.1429  
 M201: (P3) [W9] 0.1429  
 N201: (P3) [W9] 0.1429  
 O201: (P3) [W9] 0.0713  
 P201: (P4) [W11] 'N/A  
 H202: (FO) [W9] '-----  
 I202: (FO) [W11] '-----  
 J202: (FO) [W9] '-----  
 K202: (FO) [W9] '-----  
 L202: (FO) [W9] '-----  
 M202: (FO) [W9] '-----  
 N202: (FO) [W9] '-----  
 O202: (FO) [W9] '-----  
 B203: [W9] ' TAX EFFECTS OF OPTIONAL S. L.

G203: (FO) [W9] -I86  
 H203: (FO) [W9] +H201+H199  
 I203: (FO) [W11] +I201+I199  
 J203: (FO) [W9] +J201+J199  
 K203: (FO) [W9] +K201+K199  
 L203: (FO) [W9] +L201+L199  
 M203: (FO) [W9] +M201+M199  
 N203: (FO) [W9] +N201+N199  
 O203: (FO) [W9] +O201+O199  
 P203: (FO) [W11] @SUM(H203..O203)  
 B205: [W9] ' PLUS: NET CASH FLOW FROM  
 OPERATIONS  
 H205: (FO) [W9] +H183  
 I205: (FO) [W11] +I183  
 J205: (FO) [W9] +J183  
 K205: (FO) [W9] +K183  
 L205: (FO) [W9] +L183  
 M205: (FO) [W9] +M183  
 N205: (FO) [W9] +N183  
 O205: (FO) [W9] +O183  
 P205: (FO) [W11] +P183  
 H206: (FO) [W9] '-----  
 I206: (FO) [W11] '-----  
 J206: (FO) [W9] '-----  
 K206: (FO) [W9] '-----  
 L206: (FO) [W9] '-----  
 M206: (FO) [W9] '-----  
 N206: (FO) [W9] '-----  
 O206: (FO) [W9] '-----  
 P206: (FO) [W11] '-----  
 B207: [W9] 'NET INCREASE (DECREASE) IN CASH  
 FLOW  
 G207: (FO) [W9] -I86  
 H207: (FO) [W9] +H205+H203  
 I207: (FO) [W11] +I205+I203  
 J207: (FO) [W9] +J205+J203  
 K207: (FO) [W9] +K205+K203  
 L207: (FO) [W9] +L205+L203  
 M207: (FO) [W9] +M205+M203  
 N207: (FO) [W9] +N205+N203  
 O207: (FO) [W9] +O205+O203  
 P207: (FO) [W11] @SUM(H207..O207)  
 H208: (FO) [W9] '-----  
 I208: (FO) [W11] '-----  
 J208: (FO) [W9] '-----  
 K208: (FO) [W9] '-----  
 L208: (FO) [W9] '-----  
 M208: (FO) [W9] '-----  
 N208: (FO) [W9] '-----  
 O208: (FO) [W9] '-----

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P208: (F0) [W11] '-----
B213: [W9] '-----
B214: [W9] 'PRESENT VALUE SUMMARY
B215: [W9] '-----
I216: [W11] 'MACRS 5 YEAR
K216: [W9] 'S. L. 5 YEAR
H216: [W9] 'MACRS 7 YEAR
O216: [W9] 'S. L. 7 YEAR
I217: [W11] 'DEPRECIATION
K217: [W9] 'DEPRECIATION
H217: [W9] 'DEPRECIATION
O217: [W9] 'DEPRECIATION
C220: [W5] 'RECURRING OPERATIONS SAVINGS
I220: (F0) [W11] ONPV(G132,H140..H140)
K220: (F0) [W9] ONPV(G132,H140..H140)
H220: (F0) [W9] ONPV(G132,H179..O179)
O220: (F0) [W9] ONPV(G132,H179..O179)
D222: [W9] 'LESS: INCOME TAX EFFECTS
I222: (F0) [W11] ONPV(G132,H142..H142)
K222: (F0) [W9] ONPV(G132,H142..H142)
H222: (F0) [W9] ONPV(G132,H181..O181)
O222: (F0) [W9] ONPV(G132,H181..O181)
I223: (F0) [W11] '-----
K223: (F0) [W9] '-----
H223: (F0) [W9] '-----
O223: (F0) [W9] '-----
C224: [W5] 'NET CASH FLOW FROM OPERATIONS
SAVINGS
I224: (F0) [W11] ONPV(G132,H144..H144)
K224: (F0) [W9] ONPV(G132,H144..H144)
H224: (F0) [W9] ONPV(G132,H183..O183)
O224: (F0) [W9] ONPV(G132,H183..O183)
D226: [W9] 'PLUS: TAX EFFECTS OF DEPRECIATION
I226: (F0) [W11] ONPV(G132,H151..H151)
K226: (F0) [W9] ONPV(G132,H166..H166)
H226: (F0) [W9] ONPV(G132,H190..O190)
O226: (F0) [W9] ONPV(G132,H203..O203)
I227: (F0) [W11] '-----
K227: (F0) [W9] '-----
H227: (F0) [W9] '-----
O227: (F0) [W9] '-----
C228: [W5] 'TOTAL NET PRESENT VALUE OF CASH
FLOWS
I228: (F0) [W11] ONPV(G132,H155..H155)
K228: (F0) [W9] ONPV(G132,H170..H170)
H228: (F0) [W9] ONPV(G132,H194..O194)
O228: (F0) [W9] ONPV(G132,H207..O207)
C230: [W5] 'LESS: PROCUREMENT AND
INSTALLATION
I230: (F0) [W11] +186
K230: (F0) [W9] +186
H230: (F0) [W9] +186
O230: (F0) [W9] +186
I231: (F0) [W11] '-----
K231: (F0) [W9] '-----
H231: (F0) [W9] '-----
O231: (F0) [W9] '-----
C232: [W5] 'NET PRESENT VALUE
I232: (F0) [W11] +I228-I230
K232: (F0) [W9] +K228-K230
H232: (F0) [W9] +H228-H230
O232: (F0) [W9] +O228-O230
I233: (F0) [W11] '-----
K233: (F0) [W9] '-----
H233: (F0) [W9] '-----
O233: (F0) [W9] +H233
C235: [W5] 'NET PRESENT VALUE PER INSTALLED
UNIT
I235: (C0) [W11] +I232/G77
K235: (C0) [W9] +K232/G77
H235: (C0) [W9] +H232/G77
O235: (C0) [W9] +O232/G77
B237: [W9] '-----
B238: [W9] 'NPV SENSITIVITY ANALYSIS
B239: [W9] '-----
I242: [W11] 'MACRS 5 YEAR
K242: [W9] 'S. L. 5 YEAR
H242: [W9] 'MACRS 7 YEAR
O242: [W9] 'S. L. 7 YEAR
G243: [W9] 'AMOUNT
I243: [W11] 'DEPRECIATION
K243: [W9] 'DEPRECIATION
H243: [W9] 'DEPRECIATION
O243: [W9] 'DEPRECIATION
B244: [W9] 'MONTHLY CASH FLOW GAIN (LOSS)
B245: [W9] 'PER UNIT AFTER ALL EXPENSES:
G245: (C0) [W9] -40
I245: (C0) [W11]
(OPV(G245*12*G77*(1-G131),G132,6)+I226-I230)/
G77
K245: (C0) [W9]
(OPV(G245*12*G77*(1-G131),G132,6)+K226-K230)/
G77
H245: (C0) [W9]
(OPV(G245*12*G77*(1-G131),G132,6)+H226-H230)/
G77
O245: (C0) [W9]
(OPV(G245*12*G77*(1-G131),G132,6)+O226-O230)/
G77
G246: (,0) [W9] -20

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I246: (,0) [W11]  
 (OPV(G246\*12\*G77\*(1-G131),G132,6)+I226-I230)/  
 G77  
 K246: (,0) [W9]  
 (OPV(G246\*12\*G77\*(1-G131),G132,6)+K226-K230)/  
 G77  
 H246: (,0) [W9]  
 (OPV(G246\*12\*G77\*(1-G131),G132,8)+H226-H230)/  
 G77  
 O246: (,0) [W9]  
 (OPV(G246\*12\*G77\*(1-G131),G132,8)+O226-O230)/  
 G77  
 G247: (,0) [W9] 0  
 I247: (,0) [W11]  
 (OPV(G247\*12\*G77\*(1-G131),G132,6)+I226-I230)/  
 G77  
 K247: (,0) [W9]  
 (OPV(G247\*12\*G77\*(1-G131),G132,6)+K226-K230)/  
 G77  
 H247: (,0) [W9]  
 (OPV(G247\*12\*G77\*(1-G131),G132,8)+H226-H230)/  
 G77  
 O247: (,0) [W9]  
 (OPV(G247\*12\*G77\*(1-G131),G132,8)+O226-O230)/  
 G77  
 G248: (,0) [W9] 20  
 I248: (,0) [W11]  
 (OPV(G248\*12\*G77\*(1-G131),G132,6)+I226-I230)/  
 G77  
 K248: (,0) [W9]  
 (OPV(G248\*12\*G77\*(1-G131),G132,6)+K226-K230)/  
 G77  
 H248: (,0) [W9]  
 (OPV(G248\*12\*G77\*(1-G131),G132,8)+H226-H230)/  
 G77  
 O248: (,0) [W9]  
 (OPV(G248\*12\*G77\*(1-G131),G132,8)+O226-O230)/  
 G77  
 G249: (,0) [W9] 40  
 I249: (,0) [W11]  
 (OPV(G249\*12\*G77\*(1-G131),G132,6)+I226-I230)/  
 G77  
 K249: (,0) [W9]  
 (OPV(G249\*12\*G77\*(1-G131),G132,6)+K226-K230)/  
 G77  
 H249: (,0) [W9]  
 (OPV(G249\*12\*G77\*(1-G131),G132,8)+H226-H230)/  
 G77  
 O249: (,0) [W9]  
 (OPV(G249\*12\*G77\*(1-G131),G132,8)+O226-O230)/  
 G77

G77  
 G250: (,0) [W9] 60  
 I250: (,0) [W11]  
 (OPV(G250\*12\*G77\*(1-G131),G132,6)+I226-I230)/  
 G77  
 K250: (,0) [W9]  
 (OPV(G250\*12\*G77\*(1-G131),G132,6)+K226-K230)/  
 G77  
 H250: (,0) [W9]  
 (OPV(G250\*12\*G77\*(1-G131),G132,8)+H226-H230)/  
 G77  
 O250: (,0) [W9]  
 (OPV(G250\*12\*G77\*(1-G131),G132,8)+O226-O230)/  
 G77  
 G251: (,0) [W9] 80  
 I251: (,0) [W11]  
 (OPV(G251\*12\*G77\*(1-G131),G132,6)+I226-I230)/  
 G77  
 K251: (,0) [W9]  
 (OPV(G251\*12\*G77\*(1-G131),G132,6)+K226-K230)/  
 G77  
 H251: (,0) [W9]  
 (OPV(G251\*12\*G77\*(1-G131),G132,8)+H226-H230)/  
 G77  
 O251: (,0) [W9]  
 (OPV(G251\*12\*G77\*(1-G131),G132,8)+O226-O230)/  
 G77  
 G252: (,0) [W9] 100  
 I252: (,0) [W11]  
 (OPV(G252\*12\*G77\*(1-G131),G132,6)+I226-I230)/  
 G77  
 K252: (,0) [W9]  
 (OPV(G252\*12\*G77\*(1-G131),G132,6)+K226-K230)/  
 G77  
 H252: (,0) [W9]  
 (OPV(G252\*12\*G77\*(1-G131),G132,8)+H226-H230)/  
 G77  
 O252: (,0) [W9]  
 (OPV(G252\*12\*G77\*(1-G131),G132,8)+O226-O230)/  
 G77  
 G253: (,0) [W9] 120  
 I253: (,0) [W11]  
 (OPV(G253\*12\*G77\*(1-G131),G132,6)+I226-I230)/  
 G77  
 K253: (,0) [W9]  
 (OPV(G253\*12\*G77\*(1-G131),G132,6)+K226-K230)/  
 G77  
 H253: (,0) [W9]  
 (OPV(G253\*12\*G77\*(1-G131),G132,8)+H226-H230)/  
 G77

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0253:          (,0)          [W9]
(OPV(G253*12*G77*(1-G131),G132,8)+O226-O230)/
G77
G254: (,0) [W9] 140
I254:          (,0)          [W11]
(OPV(G254*12*G77*(1-G131),G132,6)+I226-I230)/
G77
K254:          (,0)          [W9]
(OPV(G254*12*G77*(1-G131),G132,6)+K226-K230)/
G77
N254:          (,0)          [W9]
(OPV(G254*12*G77*(1-G131),G132,8)+N226-N230)/
G77
O254:          (,0)          [W9]
(OPV(G254*12*G77*(1-G131),G132,8)+O226-O230)/
G77
G255: (,0) [W9] 160
I255:          (,0)          [W11]
(OPV(G255*12*G77*(1-G131),G132,6)+I226-I230)/
G77
K255:          (,0)          [W9]
(OPV(G255*12*G77*(1-G131),G132,6)+K226-K230)/
G77
N255:          (,0)          [W9]
(OPV(G255*12*G77*(1-G131),G132,8)+N226-N230)/
G77
O255:          (,0)          [W9]
(OPV(G255*12*G77*(1-G131),G132,8)+O226-O230)/
G77
G256: (,0) [W9] 180
I256:          (,0)          [W11]
(OPV(G256*12*G77*(1-G131),G132,6)+I226-I230)/
G77
K256:          (,0)          [W9]
(OPV(G256*12*G77*(1-G131),G132,6)+K226-K230)/
G77
N256:          (,0)          [W9]
(OPV(G256*12*G77*(1-G131),G132,8)+N226-N230)/
G77
O256:          (,0)          [W9]
(OPV(G256*12*G77*(1-G131),G132,8)+O226-O230)/
G77
G257: (,0) [W9] 200
I257:          (C0)          [W11]
(OPV(G257*12*G77*(1-G131),G132,6)+I226-I230)/
G77
K257:          (C0)          [W9]
(OPV(G257*12*G77*(1-G131),G132,6)+K226-K230)/
G77
N257:          (C0)          [W9]
(OPV(G257*12*G77*(1-G131),G132,8)+N226-N230)/
G77
O257:          (C0)          [W9]
(OPV(G257*12*G77*(1-G131),G132,8)+O226-O230)/
G77
B262: [W9] -----
B263: [W9] INTERNAL RATE OF RETURN ESTIMATES
B264: [W9] -----
B266: [W9] Note: A guess of the Internal
Rate of Return is required to run
B267: [W9] this module. The guess is
entered as a decimal and converted
B268: [W9] by the program to a percent
figure. An "IRR" response is
B269: [W9] displayed if the spread
sheet can not reach an IRR. In this
B270: [W9] case you should try a
different guess.
B273: [W9] IRR ESTIMATE
D273: (P2) [W9] 0.15
I273: [W11] MACRS 5 YEAR
K273: [W9] S. L. 5 YEAR
N273: [W9] MACRS 7 YEAR
O273: [W9] S. L. 7 YEAR
I274: [W11] DEPRECIATION
K274: [W9] DEPRECIATION
N274: [W9] DEPRECIATION
O274: [W9] DEPRECIATION
C276: [W5] RECURRING OPERATIONS SAVINGS
I276: (P0) [W11] @IRR(D273,G140..H140)
K276: (P0) [W9] @IRR(D273,G140..H140)
N276: (P0) [W9] @IRR(D273,G179..O179)
O276: (P0) [W9] @IRR(D273,G179..O179)
C280: [W5] AFTER TAX NET CASH FLOW FROM
OPERATIONS SAVINGS
I280: (P0) [W11] @IRR(D273,G144..H144)
K280: (P0) [W9] @IRR(D273,G144..H144)
N280: (P0) [W9] @IRR(D277,G183..O183)
O280: (P0) [W9] @IRR(D273,G183..O183)
C284: [W5] NET INCREASE (DECREASE) IN CASH
FLOW
I284: (P0) [W11] @IRR(D273,G155..H155)
K284: (P0) [W9] @IRR(D273,G170..H170)
N284: (P0) [W9] @IRR(D273,G194..O194)
O284: (P0) [W9] @IRR(D273,G207..O207)
B289: [W9] -----
B290: [W9] IRR SENSITIVITY ANALYSIS
B291: [W9] -----
Q291: -----
Q292: IRR SENSITIVITY ANALYSIS

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R293: '5 YEAR MACRS:  
 I294: [W11] 'MACRS 5 YEAR  
 K294: [W9] 'S. L. 5 YEAR  
 N294: [W9] 'MACRS 7 YEAR  
 O294: [W9] 'S. L. 7 YEAR  
 Q294: +Q291  
 G295: [W9] 'AMOUNT  
 I295: [W11] 'DEPRECIATION  
 K295: [W9] 'DEPRECIATION  
 N295: [W9] 'DEPRECIATION  
 O295: [W9] 'DEPRECIATION  
 R295: 'YEAR  
 S295: '<-----  
 T295: '-----  
 U295: '-----  
 V295: '-----  
 W295: [W9] '-----  
 X295: [W9] '----->  
 B296: [W9] 'MONTHLY CASH FLOW GAIN (LOSS)  
 B297: [W9] 'PER UNIT AFTER ALL EXPENSES:  
 G297: (C0) [W9] 0  
 I297: (P0) [W11] @IRR(D273,R298..X298)  
 K297: (P0) [W9] @IRR(D273,R312..X312)  
 N297: (P0) [W9] @IRR(D273,R338..X338)  
 O297: (P0) [W9] @IRR(D273,R361..X361)  
 R297: (F0) '0  
 S297: (F0) '1  
 T297: (F0) '2  
 U297: (F0) '3  
 V297: (F0) '4  
 W297: (F0) [W9] '5  
 X297: (F0) [W9] '6  
 G298: (,0) [W9] 20  
 I298: (P0) [W11] @IRR(D273,R299..X299)  
 K298: (P0) [W9] @IRR(D273,R313..X313)  
 N298: (P0) [W9] @IRR(D273,R339..X339)  
 O298: (P0) [W9] @IRR(D273,R362..X362)  
 R298: -189  
 S298: 12\*G297\*(1-G131)+(I89\*H149)  
 T298: 12\*G297\*(1-G131)+(I89\*I149)  
 U298: 12\*G297\*(1-G131)+(I89\*J149)  
 V298: 12\*G297\*(1-G131)+(I89\*K149)  
 W298: [W9] 12\*G297\*(1-G131)+(I89\*L149)  
 X298: [W9] 12\*G297\*(1-G131)+(I89\*M149)  
 G299: (,0) [W9] 40  
 I299: (P0) [W11] @IRR(D273,R300..X300)  
 K299: (P0) [W9] @IRR(D273,R314..X314)  
 N299: (P0) [W9] @IRR(D273,R340..X340)  
 O299: (P0) [W9] @IRR(D273,R363..X363)  
 R299: -189

S299: 12\*G298\*(1-G131)+(I89\*H149)  
 T299: 12\*G298\*(1-G131)+(I89\*I149)  
 U299: 12\*G298\*(1-G131)+(I89\*J149)  
 V299: 12\*G298\*(1-G131)+(I89\*K149)  
 W299: [W9] 12\*G298\*(1-G131)+(I89\*L149)  
 X299: [W9] 12\*G298\*(1-G131)+(I89\*M149)  
 G300: (,0) [W9] 60  
 I300: (P0) [W11] @IRR(D273,R301..X301)  
 K300: (P0) [W9] @IRR(D273,R315..X315)  
 N300: (P0) [W9] @IRR(D273,R341..X341)  
 O300: (P0) [W9] @IRR(D273,R364..X364)  
 R300: -189  
 S300: 12\*G299\*(1-G131)+(I89\*H149)  
 T300: 12\*G299\*(1-G131)+(I89\*I149)  
 U300: 12\*G299\*(1-G131)+(I89\*J149)  
 V300: 12\*G299\*(1-G131)+(I89\*K149)  
 W300: [W9] 12\*G299\*(1-G131)+(I89\*L149)  
 X300: [W9] 12\*G299\*(1-G131)+(I89\*M149)  
 G301: (,0) [W9] 80  
 I301: (P0) [W11] @IRR(D273,R302..X302)  
 K301: (P0) [W9] @IRR(D273,R316..X316)  
 N301: (P0) [W9] @IRR(D273,R342..X342)  
 O301: (P0) [W9] @IRR(D273,R365..X365)  
 R301: -189  
 S301: 12\*G300\*(1-G131)+(I89\*H149)  
 T301: 12\*G300\*(1-G131)+(I89\*I149)  
 U301: 12\*G300\*(1-G131)+(I89\*J149)  
 V301: 12\*G300\*(1-G131)+(I89\*K149)  
 W301: [W9] 12\*G300\*(1-G131)+(I89\*L149)  
 X301: [W9] 12\*G300\*(1-G131)+(I89\*M149)  
 G302: (,0) [W9] 100  
 I302: (P0) [W11] @IRR(D273,R303..X303)  
 K302: (P0) [W9] @IRR(D273,R317..X317)  
 N302: (P0) [W9] @IRR(D273,R343..X343)  
 O302: (P0) [W9] @IRR(D273,R366..X366)  
 R302: -189  
 S302: 12\*G301\*(1-G131)+(I89\*H149)  
 T302: 12\*G301\*(1-G131)+(I89\*I149)  
 U302: 12\*G301\*(1-G131)+(I89\*J149)  
 V302: 12\*G301\*(1-G131)+(I89\*K149)  
 W302: [W9] 12\*G301\*(1-G131)+(I89\*L149)  
 X302: [W9] 12\*G301\*(1-G131)+(I89\*M149)  
 G303: (,0) [W9] 120  
 I303: (P0) [W11] @IRR(D273,R304..X304)  
 K303: (P0) [W9] @IRR(D273,R318..X318)  
 N303: (P0) [W9] @IRR(D273,R344..X344)  
 O303: (P0) [W9] @IRR(D273,R367..X367)  
 R303: -189  
 S303: 12\*G302\*(1-G131)+(I89\*H149)  
 T303: 12\*G302\*(1-G131)+(I89\*I149)



U303: 12\*G302\*(1-G131)+(189\*J149)  
 V303: 12\*G302\*(1-G131)+(189\*K149)  
 W303: [W9] 12\*G303\*(1-G131)+(189\*L149)  
 X303: [W9] 12\*G302\*(1-G131)+(189\*M149)  
 G304: (,0) [W9] 149  
 I304: (P0) [W11] @IRR(D273,R305..X305)  
 K304: (P0) [W9] @IRR(D273,R319..X319)  
 M304: (P0) [W9] @IRR(D273,R345..X345)  
 O304: (P0) [W9] @IRR(D273,R368..X368)  
 R304: -189  
 S304: 12\*G303\*(1-G131)+(189\*M149)  
 T304: 12\*G303\*(1-G131)+(189\*I149)  
 U304: 12\*G303\*(1-G131)+(189\*J149)  
 V304: 12\*G303\*(1-G131)+(189\*K149)  
 W304: [W9] 12\*G303\*(1-G131)+(189\*L149)  
 X304: [W9] 12\*G303\*(1-G131)+(189\*M149)  
 G305: (,0) [W9] 168  
 I305: (P0) [W11] @IRR(D273,R306..X306)  
 K305: (P0) [W9] @IRR(D273,R320..X320)  
 M305: (P0) [W9] @IRR(D273,R346..X346)  
 O305: (P0) [W9] @IRR(D273,R369..X369)  
 R305: -189  
 S305: 12\*G304\*(1-G131)+(189\*M149)  
 T305: 12\*G304\*(1-G131)+(189\*I149)  
 U305: 12\*G304\*(1-G131)+(189\*J149)  
 V305: 12\*G304\*(1-G131)+(189\*K149)  
 W305: [W9] 12\*G304\*(1-G131)+(189\*L149)  
 X305: [W9] 12\*G304\*(1-G131)+(189\*M149)  
 G306: (,0) [W9] 188  
 I306: (P0) [W11] @IRR(D273,R307..X307)  
 K306: (P0) [W9] @IRR(D273,R321..X321)  
 M306: (P0) [W9] @IRR(D273,R347..X347)  
 O306: (P0) [W9] @IRR(D273,R370..X370)  
 R306: -189  
 S306: 12\*G305\*(1-G131)+(189\*M149)  
 T306: 12\*G305\*(1-G131)+(189\*I149)  
 U306: 12\*G305\*(1-G131)+(189\*J149)  
 V306: 12\*G305\*(1-G131)+(189\*K149)  
 W306: [W9] 12\*G305\*(1-G131)+(189\*L149)  
 X306: [W9] 12\*G305\*(1-G131)+(189\*M149)  
 G307: (,0) [W9] 208  
 I307: (P0) [W11] @IRR(D273,R308..X308)  
 K307: (P0) [W9] @IRR(D273,R322..X322)  
 M307: (P0) [W9] @IRR(D273,R348..X348)  
 O307: (P0) [W9] @IRR(D273,R371..X371)  
 R307: -189  
 S307: 12\*G306\*(1-G131)+(189\*M149)  
 T307: 12\*G306\*(1-G131)+(189\*I149)  
 U307: 12\*G306\*(1-G131)+(189\*J149)  
 V307: 12\*G306\*(1-G131)+(189\*K149)

W307: [W9] 12\*G306\*(1-G131)+(189\*L149)  
 X307: [W9] 12\*G306\*(1-G131)+(189\*M149)  
 R308: -189  
 S308: 12\*G307\*(1-G131)+(189\*M149)  
 T308: 12\*G307\*(1-G131)+(189\*I149)  
 U308: 12\*G307\*(1-G131)+(189\*J149)  
 V308: 12\*G307\*(1-G131)+(189\*K149)  
 W308: [W9] 12\*G307\*(1-G131)+(189\*L149)  
 X308: [W9] 12\*G307\*(1-G131)+(189\*M149)  
 W309: [W9] @HMAVAIL  
 B310: [W9]

R310: '5 YEAR STRAIGHT  
 R312: -189  
 S312: 12\*G297\*(1-G131)+(189\*M164)  
 T312: 12\*G297\*(1-G131)+(189\*I164)  
 U312: 12\*G297\*(1-G131)+(189\*J164)  
 V312: 12\*G297\*(1-G131)+(189\*K164)  
 W312: [W9] 12\*G297\*(1-G131)+(189\*L164)  
 X312: [W9] 12\*G297\*(1-G131)+(189\*M164)  
 G313: [W9] REVENUE AND COST INFORMATION  
 R313: -189  
 S313: 12\*G298\*(1-G131)+(189\*M164)  
 T313: 12\*G298\*(1-G131)+(189\*I164)  
 U313: 12\*G298\*(1-G131)+(189\*J164)  
 V313: 12\*G298\*(1-G131)+(189\*K164)  
 W313: [W9] 12\*G298\*(1-G131)+(189\*L164)  
 X313: [W9] 12\*G298\*(1-G131)+(189\*M164)  
 R314: -189  
 S314: 12\*G299\*(1-G131)+(189\*M164)  
 T314: 12\*G299\*(1-G131)+(189\*I164)  
 U314: 12\*G299\*(1-G131)+(189\*J164)  
 V314: 12\*G299\*(1-G131)+(189\*K164)  
 W314: [W9] 12\*G299\*(1-G131)+(189\*L164)  
 X314: [W9] 12\*G299\*(1-G131)+(189\*M164)  
 K315: [W9] \*REQURED  
 L315: [W9] \*COMPUTED  
 R315: -189  
 S315: 12\*G300\*(1-G131)+(189\*M164)  
 T315: 12\*G300\*(1-G131)+(189\*I164)  
 U315: 12\*G300\*(1-G131)+(189\*J164)  
 V315: 12\*G300\*(1-G131)+(189\*K164)  
 W315: [W9] 12\*G300\*(1-G131)+(189\*L164)  
 X315: [W9] 12\*G300\*(1-G131)+(189\*M164)  
 R316: -189  
 S316: 12\*G301\*(1-G131)+(189\*M164)  
 T316: 12\*G301\*(1-G131)+(189\*I164)

U316: 12\*G301\*(1-G131)+(I89\*J164)  
 V316: 12\*G301\*(1-G131)+(I89\*K164)  
 W316: [W9] 12\*G301\*(1-G131)+(I89\*L164)  
 X316: [W9] 12\*G301\*(1-G131)+(I89\*M164)  
 R317: -I89  
 S317: 12\*G302\*(1-G131)+(I89\*H164)  
 T317: 12\*G302\*(1-G131)+(I89\*I164)  
 U317: 12\*G302\*(1-G131)+(I89\*J164)  
 V317: 12\*G302\*(1-G131)+(I89\*K164)  
 W317: [W9] 12\*G302\*(1-G131)+(I89\*L164)  
 X317: [W9] 12\*G302\*(1-G131)+(I89\*M164)  
 C318: [W5] 'Average number of linehaul units  
 in use per month  
 K318: (,1) [W9] 446  
 R318: -I89  
 S318: 12\*G303\*(1-G131)+(I89\*H164)  
 T318: 12\*G303\*(1-G131)+(I89\*I164)  
 U318: 12\*G303\*(1-G131)+(I89\*J164)  
 V318: 12\*G303\*(1-G131)+(I89\*K164)  
 W318: [W9] 12\*G303\*(1-G131)+(I89\*L164)  
 X318: [W9] 12\*G303\*(1-G131)+(I89\*M164)  
 R319: -I89  
 S319: 12\*G304\*(1-G131)+(I89\*H164)  
 T319: 12\*G304\*(1-G131)+(I89\*I164)  
 U319: 12\*G304\*(1-G131)+(I89\*J164)  
 V319: 12\*G304\*(1-G131)+(I89\*K164)  
 W319: [W9] 12\*G304\*(1-G131)+(I89\*L164)  
 X319: [W9] 12\*G304\*(1-G131)+(I89\*M164)  
 C320: [W5] 'Average revenue per mile  
 K320: (C3) [W9] 1.58  
 R320: -I89  
 S320: 12\*G305\*(1-G131)+(I89\*H164)  
 T320: 12\*G305\*(1-G131)+(I89\*I164)  
 U320: 12\*G305\*(1-G131)+(I89\*J164)  
 V320: 12\*G305\*(1-G131)+(I89\*K164)  
 W320: [W9] 12\*G305\*(1-G131)+(I89\*L164)  
 X320: [W9] 12\*G305\*(1-G131)+(I89\*M164)  
 R321: -I89  
 S321: 12\*G306\*(1-G131)+(I89\*H164)  
 T321: 12\*G306\*(1-G131)+(I89\*I164)  
 U321: 12\*G306\*(1-G131)+(I89\*J164)  
 V321: 12\*G306\*(1-G131)+(I89\*K164)  
 W321: [W9] 12\*G306\*(1-G131)+(I89\*L164)  
 X321: [W9] 12\*G306\*(1-G131)+(I89\*M164)  
 C322: [W5] 'Average variable operating  
 expenses per mile  
 K322: (C3) [W9] 1.32  
 R322: -I89  
 S322: 12\*G307\*(1-G131)+(I89\*H164)  
 T322: 12\*G307\*(1-G131)+(I89\*I164)

U322: 12\*G307\*(1-G131)+(I89\*J164)  
 V322: 12\*G307\*(1-G131)+(I89\*K164)  
 W322: [W9] 12\*G307\*(1-G131)+(I89\*L164)  
 X322: [W9] 12\*G307\*(1-G131)+(I89\*M164)  
 C324: [W5] 'Average contribution  
 L324: (C3) [W9] +K320-K322  
 Q324: '-----  
 B327: [W9]  
 '-----  
 '-----  
 '-----  
 K330: [W9] 'REVENUE INCREASES  
 Q332: 'IRR SENSITIVITY ANALYSIS  
 B333: [W9] 'Premium service:  
 R333: '7 YEAR HACHS:  
 Q334: +Q324  
 C335: [W5] 'Existing premium service revenues  
 per month  
 K335: (C0) [W9] 0  
 R335: 'YEAR  
 S335: '<-----  
 T335: '-----  
 U335: '-----  
 V335: '-----  
 W335: [W9] '-----  
 X335: [W9] '-----  
 C337: [W5] 'Projected improvement with the  
 satellite system (X)  
 K337: (P0) [W9] 0  
 R337: (P0) "0  
 S337: (P0) "1  
 T337: (P0) "2  
 U337: (P0) "3  
 V337: (P0) "4  
 W337: (P0) [W9] "5  
 X337: (P0) [W9] "6  
 Y337: (P0) [W9] "7  
 Z337: (P0) [W9] "8  
 R338: -I89  
 S338: 12\*G297\*(1-G131)+(I89\*H188)  
 T338: 12\*G297\*(1-G131)+(I89\*I188)  
 U338: 12\*G297\*(1-G131)+(I89\*J188)  
 V338: 12\*G297\*(1-G131)+(I89\*K188)  
 W338: [W9] 12\*G297\*(1-G131)+(I89\*L188)  
 X338: [W9] 12\*G297\*(1-G131)+(I89\*M188)  
 Y338: [W9] 12\*G297\*(1-G131)+(I89\*O188)  
 Z338: [W9] 12\*G297\*(1-G131)+(I89\*Q188)  
 C339: [W5] 'Sales and marketing expense ratio  
 (X)

K339: (P0) [W9] 0  
 R339: -I89  
 S339: 12\*G298\*(1-G131)+(I89\*H188)  
 T339: 12\*G298\*(1-G131)+(I89\*I188)  
 U339: 12\*G298\*(1-G131)+(I89\*J188)  
 V339: 12\*G298\*(1-G131)+(I89\*K188)  
 W339: [W9] 12\*G298\*(1-G131)+(I89\*L188)  
 X339: [W9] 12\*G298\*(1-G131)+(I89\*H188)  
 Y339: [W9] 12\*G298\*(1-G131)+(I89\*H188)  
 Z339: [W9] 12\*G298\*(1-G131)+(I89\*O188)  
 R340: -I89  
 S340: 12\*G299\*(1-G131)+(I89\*H188)  
 T340: 12\*G299\*(1-G131)+(I89\*I188)  
 U340: 12\*G299\*(1-G131)+(I89\*J188)  
 V340: 12\*G299\*(1-G131)+(I89\*K188)  
 W340: [W9] 12\*G299\*(1-G131)+(I89\*L188)  
 X340: [W9] 12\*G299\*(1-G131)+(I89\*H188)  
 Y340: [W9] 12\*G299\*(1-G131)+(I89\*H188)  
 Z340: [W9] 12\*G299\*(1-G131)+(I89\*O188)  
 C341: [W5] 'Current premium service costs per month  
 K341: (C0) [W9] 0  
 R341: -I89  
 S341: 12\*G300\*(1-G131)+(I89\*H188)  
 T341: 12\*G300\*(1-G131)+(I89\*I188)  
 U341: 12\*G300\*(1-G131)+(I89\*J188)  
 V341: 12\*G300\*(1-G131)+(I89\*K188)  
 W341: [W9] 12\*G300\*(1-G131)+(I89\*L188)  
 X341: [W9] 12\*G300\*(1-G131)+(I89\*H188)  
 Y341: [W9] 12\*G300\*(1-G131)+(I89\*H188)  
 Z341: [W9] 12\*G300\*(1-G131)+(I89\*O188)  
 R342: -I89  
 S342: 12\*G301\*(1-G131)+(I89\*H188)  
 T342: 12\*G301\*(1-G131)+(I89\*I188)  
 U342: 12\*G301\*(1-G131)+(I89\*J188)  
 V342: 12\*G301\*(1-G131)+(I89\*K188)  
 W342: [W9] 12\*G301\*(1-G131)+(I89\*L188)  
 X342: [W9] 12\*G301\*(1-G131)+(I89\*H188)  
 Y342: [W9] 12\*G301\*(1-G131)+(I89\*H188)  
 Z342: [W9] 12\*G301\*(1-G131)+(I89\*O188)  
 C343: [W5] 'Projected increase in premium service costs (%)  
 K343: (P0) [W9] 0  
 R343: -I89  
 S343: 12\*G302\*(1-G131)+(I89\*H188)  
 T343: 12\*G302\*(1-G131)+(I89\*I188)  
 U343: 12\*G302\*(1-G131)+(I89\*J188)  
 V343: 12\*G302\*(1-G131)+(I89\*K188)  
 W343: [W9] 12\*G302\*(1-G131)+(I89\*L188)  
 X343: [W9] 12\*G302\*(1-G131)+(I89\*H188)  
 Y343: [W9] 12\*G302\*(1-G131)+(I89\*H188)  
 Z343: [W9] 12\*G302\*(1-G131)+(I89\*O188)  
 R344: -I89  
 S344: 12\*G303\*(1-G131)+(I89\*H188)  
 T344: 12\*G303\*(1-G131)+(I89\*I188)  
 U344: 12\*G303\*(1-G131)+(I89\*J188)  
 V344: 12\*G303\*(1-G131)+(I89\*K188)  
 W344: [W9] 12\*G303\*(1-G131)+(I89\*L188)  
 X344: [W9] 12\*G303\*(1-G131)+(I89\*H188)  
 Y344: [W9] 12\*G303\*(1-G131)+(I89\*H188)  
 Z344: [W9] 12\*G303\*(1-G131)+(I89\*O188)  
 D345: [W9] 'Increase in Marketing revenues per month  
 L345: (C0) [W9] +K335\*K337  
 R345: -I89  
 S345: 12\*G304\*(1-G131)+(I89\*H188)  
 T345: 12\*G304\*(1-G131)+(I89\*I188)  
 U345: 12\*G304\*(1-G131)+(I89\*J188)  
 V345: 12\*G304\*(1-G131)+(I89\*K188)  
 W345: [W9] 12\*G304\*(1-G131)+(I89\*L188)  
 X345: [W9] 12\*G304\*(1-G131)+(I89\*H188)  
 Y345: [W9] 12\*G304\*(1-G131)+(I89\*H188)  
 Z345: [W9] 12\*G304\*(1-G131)+(I89\*O188)  
 R346: -I89  
 S346: 12\*G305\*(1-G131)+(I89\*H188)  
 T346: 12\*G305\*(1-G131)+(I89\*I188)  
 U346: 12\*G305\*(1-G131)+(I89\*J188)  
 V346: 12\*G305\*(1-G131)+(I89\*K188)  
 W346: [W9] 12\*G305\*(1-G131)+(I89\*L188)  
 X346: [W9] 12\*G305\*(1-G131)+(I89\*H188)  
 Y346: [W9] 12\*G305\*(1-G131)+(I89\*H188)  
 Z346: [W9] 12\*G305\*(1-G131)+(I89\*O188)  
 D347: [W9] 'Applied sales and marketing expense ratio  
 L347: (C0) [W9] +K339\*L345  
 R347: -I89  
 S347: 12\*G306\*(1-G131)+(I89\*H188)  
 T347: 12\*G306\*(1-G131)+(I89\*I188)  
 U347: 12\*G306\*(1-G131)+(I89\*J188)  
 V347: 12\*G306\*(1-G131)+(I89\*K188)  
 W347: [W9] 12\*G306\*(1-G131)+(I89\*L188)  
 X347: [W9] 12\*G306\*(1-G131)+(I89\*H188)  
 Y347: [W9] 12\*G306\*(1-G131)+(I89\*H188)  
 Z347: [W9] 12\*G306\*(1-G131)+(I89\*O188)  
 R348: -I89  
 S348: 12\*G307\*(1-G131)+(I89\*H188)  
 T348: 12\*G307\*(1-G131)+(I89\*I188)  
 U348: 12\*G307\*(1-G131)+(I89\*J188)  
 V348: 12\*G307\*(1-G131)+(I89\*K188)  
 W348: [W9] 12\*G307\*(1-G131)+(I89\*L188)

X348: [W9] 12\*G307\*(1-G131)+(I89\*H188)  
 Y348: [W9] 12\*G307\*(1-G131)+(I89\*H188)  
 Z348: [W9] 12\*G307\*(1-G131)+(I89\*O188)  
 D349: [W9] 'Projected cost increase per month  
 L349: (C0) [W9] +K341+K343  
 D351: [W9] 'Contribution per linehaul unit per  
 month  
 L351: (C2) [W9] (L345-L347-L349)/K318  
 R352: '7 YEAR STRAIGHT  
 B353: [W9] 'Miscellaneous  
 C355: [W5] 'Total miscellaneous contribution  
 increase per month  
 K355: (C0) [W9] 0  
 D357: [W9] 'Miscellaneous contribution per  
 line haul unit per month  
 L357: (C2) [W9] +K355/K318  
 B359: [W9]

**R361: [W9] 'EXPENSE REDUCTION MODCUE**

R361: -I89  
 S361: 12\*G297\*(1-G131)+(I89\*H201)  
 T361: 12\*G297\*(1-G131)+(I89\*I201)  
 U361: 12\*G297\*(1-G131)+(I89\*J201)  
 V361: 12\*G297\*(1-G131)+(I89\*K201)  
 W361: [W9] 12\*G297\*(1-G131)+(I89\*L201)  
 X361: [W9] 12\*G297\*(1-G131)+(I89\*H201)  
 Y361: [W9] 12\*G297\*(1-G131)+(I89\*H201)  
 Z361: [W9] 12\*G297\*(1-G131)+(I89\*O201)  
 R362: -I89  
 S362: 12\*G298\*(1-G131)+(I89\*H201)  
 T362: 12\*G298\*(1-G131)+(I89\*I201)  
 U362: 12\*G298\*(1-G131)+(I89\*J201)  
 V362: 12\*G298\*(1-G131)+(I89\*K201)  
 W362: [W9] 12\*G298\*(1-G131)+(I89\*L201)  
 X362: [W9] 12\*G298\*(1-G131)+(I89\*H201)  
 Y362: [W9] 12\*G298\*(1-G131)+(I89\*H201)  
 Z362: [W9] 12\*G298\*(1-G131)+(I89\*O201)  
 B363: [W9] 'Deadhead reduction:  
 L363: [W9] 'REQUIRED  
 L363: [W9] 'COMPUTED  
 R363: -I89  
 S363: 12\*G299\*(1-G131)+(I89\*H201)  
 T363: 12\*G299\*(1-G131)+(I89\*I201)  
 U363: 12\*G299\*(1-G131)+(I89\*J201)  
 V363: 12\*G299\*(1-G131)+(I89\*K201)  
 W363: [W9] 12\*G299\*(1-G131)+(I89\*L201)  
 X363: [W9] 12\*G299\*(1-G131)+(I89\*H201)

Y363: [W9] 12\*G299\*(1-G131)+(I89\*H201)  
 Z363: [W9] 12\*G299\*(1-G131)+(I89\*O201)  
 R364: -I89  
 S364: 12\*G300\*(1-G131)+(I89\*H201)  
 T364: 12\*G300\*(1-G131)+(I89\*I201)  
 U364: 12\*G300\*(1-G131)+(I89\*J201)  
 V364: 12\*G300\*(1-G131)+(I89\*K201)  
 W364: [W9] 12\*G300\*(1-G131)+(I89\*L201)  
 X364: [W9] 12\*G300\*(1-G131)+(I89\*H201)  
 Y364: [W9] 12\*G300\*(1-G131)+(I89\*H201)  
 Z364: [W9] 12\*G300\*(1-G131)+(I89\*O201)  
 C365: [W5] 'Average number of miles per month  
 per linehaul unit  
 K365: (,0) [W9] 5952  
 R365: -I89  
 S365: 12\*G301\*(1-G131)+(I89\*H201)  
 T365: 12\*G301\*(1-G131)+(I89\*I201)  
 U365: 12\*G301\*(1-G131)+(I89\*J201)  
 V365: 12\*G301\*(1-G131)+(I89\*K201)  
 W365: [W9] 12\*G301\*(1-G131)+(I89\*L201)  
 X365: [W9] 12\*G301\*(1-G131)+(I89\*H201)  
 Y365: [W9] 12\*G301\*(1-G131)+(I89\*H201)  
 Z365: [W9] 12\*G301\*(1-G131)+(I89\*O201)  
 R366: -I89  
 S366: 12\*G302\*(1-G131)+(I89\*H201)  
 T366: 12\*G302\*(1-G131)+(I89\*I201)  
 U366: 12\*G302\*(1-G131)+(I89\*J201)  
 V366: 12\*G302\*(1-G131)+(I89\*K201)  
 W366: [W9] 12\*G302\*(1-G131)+(I89\*L201)  
 X366: [W9] 12\*G302\*(1-G131)+(I89\*H201)  
 Y366: [W9] 12\*G302\*(1-G131)+(I89\*H201)  
 Z366: [W9] 12\*G302\*(1-G131)+(I89\*O201)  
 C367: [W5] 'Average loaded miles (%)  
 K367: (P0) [W9] 0.85  
 R367: -I89  
 S367: 12\*G303\*(1-G131)+(I89\*H201)  
 T367: 12\*G303\*(1-G131)+(I89\*I201)  
 U367: 12\*G303\*(1-G131)+(I89\*J201)  
 V367: 12\*G303\*(1-G131)+(I89\*K201)  
 W367: [W9] 12\*G303\*(1-G131)+(I89\*L201)  
 X367: [W9] 12\*G303\*(1-G131)+(I89\*H201)  
 Y367: [W9] 12\*G303\*(1-G131)+(I89\*H201)  
 Z367: [W9] 12\*G303\*(1-G131)+(I89\*O201)  
 R368: -I89  
 S368: 12\*G304\*(1-G131)+(I89\*H201)  
 T368: 12\*G304\*(1-G131)+(I89\*I201)  
 U368: 12\*G304\*(1-G131)+(I89\*J201)  
 V368: 12\*G304\*(1-G131)+(I89\*K201)  
 W368: [W9] 12\*G304\*(1-G131)+(I89\*L201)  
 X368: [W9] 12\*G304\*(1-G131)+(I89\*H201)

Y368: [W9] 12*G304*(1-G131)+(189*H201)	per month
Z368: [W9] 12*G304*(1-G131)+(189*Q201)	K383: (,1) [W9] 0
D369: [W9] 'Average loaded miles	C385: [W5] 'Projected improvement with
L369: (,0) [W9] +K365*K367	satellite system in hours per month
R369: -189	K385: (,1) [W9] 17
S369: 12*G305*(1-G131)+(189*H201)	C387: [W5] 'Average speed in MPH
T369: 12*G305*(1-G131)+(189*I201)	K387: (,1) [W9] 40
U369: 12*G305*(1-G131)+(189*J201)	D389: [W9] 'Average miles per driver per month
V369: 12*G305*(1-G131)+(189*K201)	L389: (,0) [W9] +K387*K381
W369: [W9] 12*G305*(1-G131)+(189*L201)	D391: [W9] 'Increase in total miles per month
X369: [W9] 12*G305*(1-G131)+(189*M201)	per driver at average speed
Y369: [W9] 12*G305*(1-G131)+(189*N201)	L391: (,0) [W9] +K385*K387
Z369: [W9] 12*G305*(1-G131)+(189*O201)	D393: [W9] 'Increase in loaded miles per
R370: -189	driver per month
S370: 12*G306*(1-G131)+(189*H201)	L393: (,0) [W9] (K367+K371)*L391
T370: 12*G306*(1-G131)+(189*I201)	D395: [W9] 'Improvement in revenue per driver
U370: 12*G306*(1-G131)+(189*J201)	per month
V370: 12*G306*(1-G131)+(189*K201)	L395: (C0) [W9] +L393*K320
W370: [W9] 12*G306*(1-G131)+(189*L201)	D397: [W9] 'Variable expense per driver per
X370: [W9] 12*G306*(1-G131)+(189*M201)	month impact
Y370: [W9] 12*G306*(1-G131)+(189*N201)	L397: (C0) [W9] +K322*L391
Z370: [W9] 12*G306*(1-G131)+(189*O201)	D399: [W9] 'Increase in contribution per
C371: [W5] 'Estimated increase in loaded miles	driver per month
(%)	L399: (C0) [W9] +L395-L397
K371: (P0) [W9] 0.1	D401: [W9] 'Increase in contribution per
R371: -189	linehaul unit per month
S371: 12*G307*(1-G131)+(189*H201)	L401: (C2) [W9] +K379/K318*L399
T371: 12*G307*(1-G131)+(189*I201)	B403: [W9] 'Layover pay:
U371: 12*G307*(1-G131)+(189*J201)	K403: [W9] 'REQUIRED
V371: 12*G307*(1-G131)+(189*K201)	L403: [W9] 'COMPUTED
W371: [W9] 12*G307*(1-G131)+(189*L201)	C405: [W5] 'Total layover pay per month
X371: [W9] 12*G307*(1-G131)+(189*M201)	K405: (C2) [W9] 0
Y371: [W9] 12*G307*(1-G131)+(189*N201)	C407: [W5] 'Estimated average reduction (%)
Z371: [W9] 12*G307*(1-G131)+(189*O201)	K407: (P0) [W9] 0
C373: [W5] 'Estimated loaded miles per month	D409: [W9] 'Projected layover expense
D373: [W9] (1+K371)*L369	reduction
L373: (,0) [W9] (1+K371)*L369	L409: (C2) [W9] +K405*K407
D375: [W9] 'Estimated increase in contribution	D411: [W9] 'Average number of linehaul units
per month	per month
L375: (C2) [W9] +K371*L369*L324	L411: (,1) [W9] +K318
B377: [W9] 'Driver and equipment productivity:	D413: [W9] 'Reduction in average layover
K377: [W9] 'REQUIRED	expense per linehaul unit
L377: [W9] 'COMPUTED	L413: (C2) [W9] +L409/L411
C379: [W5] 'Average number of linehaul drivers	B415: [W9] 'Dispatcher productivity:
per month	K415: [W9] 'REQUIRED
K379: (,1) [W9] 446	L415: [W9] 'COMPUTED
C381: [W5] 'Average on-duty driving hours per	C417: [W5] 'Existing dispatcher hours per
month	month
K381: (,1) [W9] 168	K417: (,1) [W9] 0
C383: [W5] 'Average on-duty NON-driving hours	C419: [W5] 'Projected reduction with satellite

system (%)  
 K419: (P0) [W9] 0  
 C421: [W5] 'Average dispatcher wages and  
 fringes per hour  
 K421: (C2) [W9] 0  
 D423: [W9] 'Projected impact in hours per  
 month  
 L423: (,1) [W9] +K419\*K417  
 D425: [W9] 'Projected monthly reduction in  
 labor costs  
 L425: (C2) [W9] +L423\*K421  
 D427: [W9] 'Average number of linehaul units  
 per month  
 L427: (,1) [W9] +K318  
 D429: [W9] 'Reduction of dispatcher wages and  
 fringes  
 K430: [W9] 'per linehaul unit per month  
 L430: (C2) [W9] +L425/K318  
 B432: [W9] 'Security, Safety, and Insurance:  
 K432: [W9] 'REQUIRED  
 L432: [W9] 'COMPUTED  
 C434: [W5] 'Total insurance premium expense  
 per month  
 K434: (C0) [W9] 0  
 C436: [W5] 'Estimated premium reduction (%)  
 K436: (P0) [W9] 0  
 D438: [W9] 'Projected premium savings per  
 month  
 L438: (C2) [W9] +K434\*K436  
 C440: [W5] 'Total claims expense per month  
 K440: (C0) [W9] 0  
 C442: [W5] 'Estimated claims reduction (%)  
 K442: (P0) [W9] 0  
 D444: [W9] 'Projected claims savings per month  
 L444: (C2) [W9] +K440\*K442  
 D446: [W9] 'Total insurance premium and claims  
 savings per month  
 L446: (C2) [W9] +L438+L444  
 D448: [W9] 'Insurance and claims expense  
 reduction per linehaul  
 D449: [W9] 'unit per month  
 L449: (C2) [W9] +L446/K318  
 B451: [W9] 'Administrative expenses:  
 K451: [W9] 'REQUIRED  
 L451: [W9] 'COMPUTED  
 C453: [W5] 'Existing administrative expenses  
 per month  
 K453: (C2) [W9] 0  
 C455: [W5] 'Projected improvement with  
 satellite system (%)  
 K455: (P0) [W9] 0  
 D457: [W9] 'Estimated monthly administrative  
 expense reduction  
 L457: (C2) [W9] +K453\*K455  
 D459: [W9] 'Estimated monthly admin expense  
 reduction per  
 D460: [W9] 'linehaul unit per month  
 L460: (C2) [W9] +L457/K318  
 B462: [W9] 'Telecommunications expense:  
 K462: [W9] 'REQUIRED  
 L462: [W9] 'COMPUTED  
 C464: [W5] 'Existing telephone expense per  
 linehaul unit per month  
 K464: (C2) [W9] 64.66  
 C466: [W5] 'Projected reduction with satellite  
 system (%)  
 K466: (P2) [W9] 0.6  
 D468: [W9] 'Estimated reduction per month  
 L468: (C2) [W9] +K466\*K464  
 B470: [W9] 'Miscellaneous:  
 C472: [W5] 'Estimated reduction in  
 miscellaneous expenses  
 K472: (C2) [W9] 0  
 D474: [W9] 'Estimated reduction per linehaul  
 unit per month  
 L474: (C2) [W9] +K472/K318  
 B476: [W9]  
 \_\_\_\_\_  
 \_\_\_\_\_  
 D478: [W9] 'COST INCREASES MODULE  
 B480: [W9] 'Monthly charges for the satellite  
 service:  
 K480: [W9] 'REQUIRED  
 L480: [W9] 'COMPUTED  
 C482: [W5] 'Monthly charge per installed unit  
 K482: (C2) [W9] 150  
 C484: [W5] 'Equipment lease expenses per unit  
 (if required)  
 K484: (C2) [W9] 0  
 C486: [W5] 'Nationwide pager service per unit  
 (if required)  
 K486: (C2) [W9] 0  
 D488: [W9] 'Total  
 L488: (C2) [W9] @SUM(K482..K486)  
 B490: [W9] 'Telecommunications expenses:  
 K490: [W9] 'REQUIRED  
 L490: [W9] 'COMPUTED  
 C492: [W5] 'Total estimated costs for

communication with  
 D493: [W9] 'the network management center  
 K493: (C2) [W9] 785.4  
 D495: [W9] 'Estimated costs per linehaul unit  
 L495: (C2) [W9] +K493/K318  
 B497: [W9] 'Maintenance expense PER YEAR:  
 K497: [W9] 'REQUIRED  
 L497: [W9] 'COMPUTED  
 C499: [W5] 'Office equipment  
 K499: (C2) [W9] 0  
 C501: [W5] 'Software updates  
 K501: (C2) [W9] 0  
 C503: [W5] 'Per linehaul unit  
 K503: (C2) [W9] 50  
 D505: [W9] 'Cost per linehaul unit per month  
 L505: (C2) [W9]  

$$(K499+K501+(K503*K318))/K318/12$$
  
 B507: [W9] 'Miscellaneous  
 C509: [W5] 'Total miscellaneous cost increases  
 per month  
 K509: (C0) [W9] 0  
 D511: [W9] 'Miscellaneous cost increases per  
 linehaul unit per month  
 L511: (C2) [W9] +K509/K318

## APPENDIX D

### OPERATING STATISTICS AND COST ANALYSIS

#### A. PURPOSE

Consolidated motor-carrier operating data are used to derive qualitative operating statistics, costs, and revenues for a model firm in six segments of the trucking industry. The model firm data are used in a qualitative analysis to determine if mobile satellite systems may make sense for use in various segments of the trucking industry. Qualitative analysis is stressed because the model firm statistics are the result of averages and an inexact fixed and variable cost model. These figures are undoubtedly different from what actually occurs in any specific form.

#### B. DATA

The motor carrier industry operating statistics and costs used in the analysis are listed in Table 33. Class I carriers are defined as those companies which have an annual revenue of \$5,000,000 or more. Class II carriers have a yearly revenue less than class I but greater than \$1,000,000. Class III carriers are those firms which have annual revenues less than \$1,000,000 and are not included in the analysis. Also not included in the analysis are private trucking fleets and household goods carriers.



### C. DATA ANALYSIS

To ensure the analysis is conservative, operating costs are computed from two sources of data in the ATA report. One set of per-mile operating costs is determined by dividing the linehaul cost category amount (line 95) by the number of linehaul miles driven (line 112). A variable and fixed cost model is also constructed. As shown in Figure 168, this model allocates expenses associated with operating vehicles as variable costs and all other expenses as fixed costs. Fixed costs are those expenses which do not change during a time period despite a change in the total number of trucks operated and distance traveled. Variable costs change in direct proportion to the number of trucks operated and the total distance traveled. Fixed and variable costs are indicated in the cost category (second column) of Table 33. Depreciation is not taken into account.

Model firm operating statistics, costs, and revenues are computed in the last section of Table 33. The following data are used in the analysis:

<u>Description</u>	<u>Line Number</u>
Average number of linehaul units	449
Intercity operating revenue per mile	201
Average miles per power unit	239
Communications expense per power unit	255
Variable operating costs per mile	221 & 263 (which ever is greater)

# FIXED AND VARIABLE COST MODEL

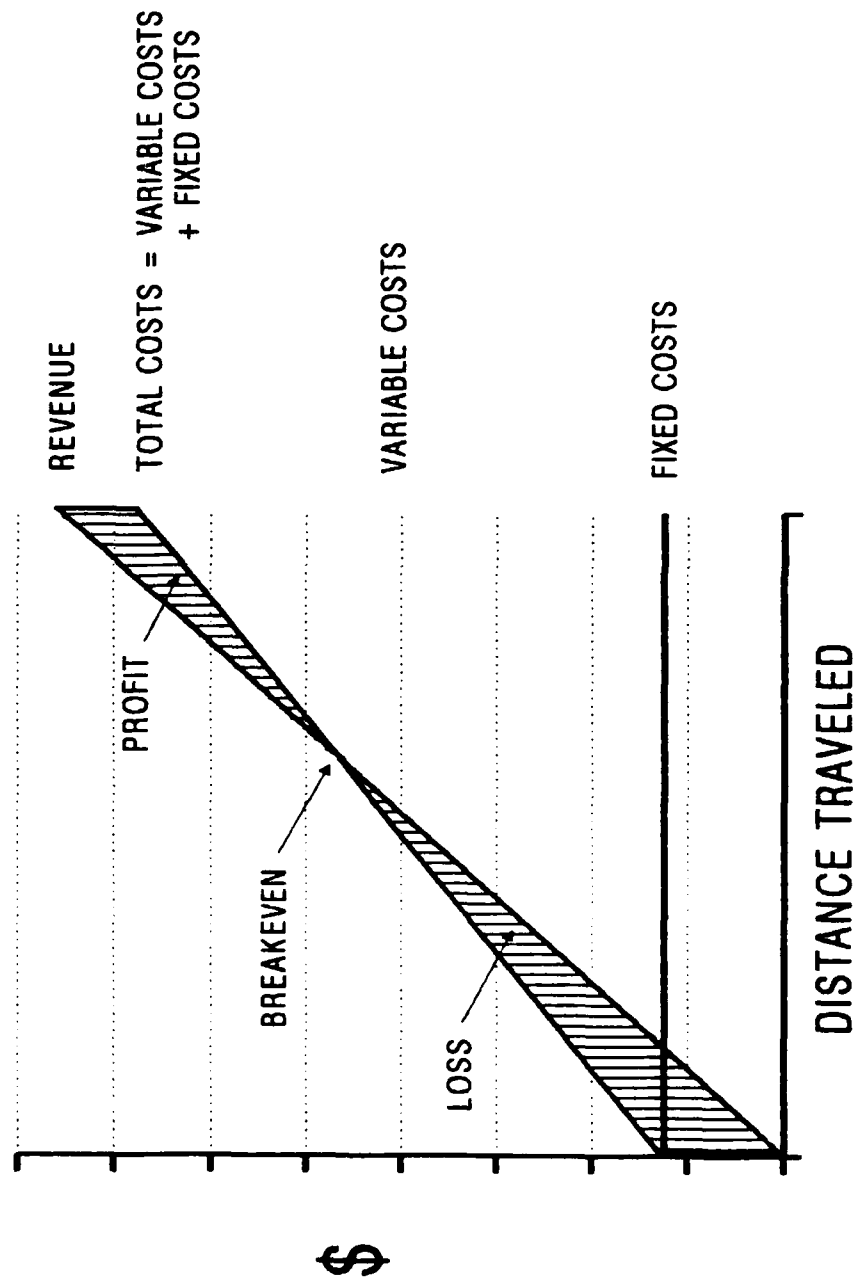


Figure 168. Fixed and Variable Cost Model

TABLE 33

Extracts from the American Trucking Associations 1986 Motor Carrier Annual Report  
Results of Operations, Class I and II, Motor Carriers  
of Property Regulated by the Interstate Commerce Commission

ALL DOLLAR FIGURES/MILEAGE IN 000's

LINE NR.	COST CAT.	ITEM	GENERAL FREIGHT		SPECIALIZED COMMON OTHER THAN GEN FRT		CONTRACT SPECIAL COMMODITY	
			CLASS I	CLASS II	CLASS I	CLASS II	CLASS I	CLASS II
10		REV - INTER COMMON	\$16,045,876	\$957,166	\$4,804,810	\$1,273,368	\$48,255	\$75,741
11		REV - INTR CONTRACT	864,014	122,641	420,143	62,484	902,023	279,645
12		REV- LOCAL CARTAGE	107,857	37,623	78,416	30,800	67,446	11,048
13		REV- FOR OTHER CARRIER	44,098	25,321	47,943	23,692	57,088	4,581
14		(MOVING REVENUE)	486	1,587	1,967	0	0	0
15		OTHER	122,933	31,605	79,322	62,204	17,355	7,264
16		TOTAL OPERATING REVENUE	\$17,185,264	\$1,175,943	\$5,432,601	\$1,452,548	\$1,092,167	\$378,279
17								
18		OWNED TRUCKS	10,249	1,888	2,434	2,077	3,771	389
19		OWNED TRACTORS	85,347	6,850	21,839	7,265	4,207	1,857
20		OWNED TRAILERS	259,569	18,206	61,334	22,069	11,174	5,273
21								
22		TOTAL POWER UNITS - INTERCITY	118,210	13,008	53,835	15,244	9,815	3,979
23		OWNED POWER UNITS - INTERCITY	89,313	8,090	23,804	8,886	8,005	2,120
24		VEH RENTED W/DRIVER	16,700	3,413	19,563	5,060	828	1,241
25		VEH RENTED W/C DRIVER	12,197	1,505	10,468	1,298	982	618
26								
27		RET ON XPN INVEST	10.19%	12.11%	6.76%	9.00%	7.51%	8.01%
28		RET ON EQUITY	12.77%	16.10%	9.21%	11.73%	14.24%	9.76%
29		RET ON CAPITAL	9.63%	10.83%	5.96%	7.77%	7.85%	7.38%
30								
31								
32	FC	SALARIES - OFF AND SUPER	\$1,500,794	\$62,827	\$238,422	\$63,231	\$40,607	\$15,716
33								
34	VC	DRIVERS/HELPERS	\$3,314,134	\$184,420	\$744,732	\$205,702	\$236,122	\$63,751
35	VC	OWNER-OPERATOR	68,949	7,419	57,243	4,243	2,971	969
36	VC	VEH REPAIR/SERVICE	328,775	20,029	123,013	31,024	32,788	8,733
37	FC	CLERICAL AND ADMIN	604,132	37,056	96,229	30,843	22,091	6,637
38	FC	OTHER	842,677	14,187	(16,706)	661	792	(398)
39		TOTAL SAL AND WAGES	\$5,158,667	\$263,111	\$1,004,511	\$272,472	\$294,764	\$79,692
40								
41	VC	PRO RATED VC OF TIME OFF	\$378,515	\$9,735	\$57,852	\$6,281	\$30,824	\$2,624
42	FC	PRO RATED FC OF TIME OFF	147,538	2,354	4,974	821	2,594	223
43		TOT MISC PAID TIME OFF	526,053	12,089	62,826	7,102	33,418	2,847
44		TOTAL SAL, WAGES, MISC T.O.	\$5,684,721	\$275,200	\$1,067,337	\$279,575	\$328,182	\$82,539
45								
46		OTHER FRINGES	\$1,689,028	\$62,431	\$276,647	\$60,759	\$87,936	\$18,756
47		WORKMAN'S COMP	291,100	14,112	79,052	18,499	23,974	5,234
48		TOTAL FRINGES	1,980,128	76,543	355,699	79,258	111,910	23,990
49	VC	PRO RATED VC OF FRINGES	1,424,778	61,636	327,540	70,094	103,222	22,112
50	FC	PRO RATED FC OF FRINGES	555,350	14,907	28,159	9,164	8,688	1,878
51								
52		GRAND TOTAL COMP	\$7,664,849	\$351,743	\$1,423,036	\$358,833	\$440,092	\$106,529
53								

TABLE 33 (CONTINUED)

ALL DOLLAR FIGURES/MILEAGE IN 000's

LINE NR.	COST CAT.	ITEM	GENERAL FREIGHT		SPECIALIZED COMMON OTHER THAN GEN FRT		CONTRACT SPECIAL COMMODITY	
			CLASS I	CLASS II	CLASS I	CLASS II	CLASS I	CLASS II
54	VC	OTHER OP SUPPLIES/EXP	\$296,316	\$17,036	\$131,563	\$28,977	\$25,648	\$8,275
55	VC	FUEL- HW	605,000	68,357	249,482	93,771	67,368	26,477
56	VC	OIL, LUBE, COOLANTS	24,177	1,974	10,557	2,666	1,906	576
57	VC	VEHICLE PARTS	243,191	29,730	120,554	51,756	25,633	11,360
58	VC	VEH MAINT/OUT SIDE REP	186,786	12,932	71,297	16,947	15,127	5,343
59	VC	TIRES AND TUBES	177,162	17,480	84,185	24,938	18,998	6,489
60		TOTAL OPP SUPP AND EXP	\$1,532,632	\$147,509	\$667,638	\$219,055	\$154,680	\$58,520
61								
62	FC	TOT GEN OP SUPPLY AND EXP	\$791,465	\$48,022	\$196,377	\$42,226	\$49,722	\$9,520
63								
64	FC	OTHER TAX AND LIC	\$77,086	\$4,920	\$17,641	\$6,034	\$3,555	\$1,437
65	VC	POL ST AND FED	285,135	21,300	100,102	29,849	18,583	8,795
66	FC	LIC AND REG FEES	204,944	17,024	90,085	25,905	22,054	5,873
67		TOTAL OPER TAX & LIC	\$567,165	\$43,244	\$207,828	\$61,788	\$44,192	\$16,105
68								
69	FC	OTHER INSURANCE	\$23,954	\$5,003	\$5,949	\$5,510	\$4,365	\$928
70	FC	PL & PD	230,252	31,215	177,231	50,097	22,883	13,166
71	FC	CARGO LOSS AND DAMAGE	205,535	7,690	51,680	8,772	15,054	1,928
72	FC	FIRE, THEFT, COLL	21,403	5,851	18,018	8,683	1,830	3,012
73		TOTAL INSURANCE	\$481,164	\$49,759	\$252,878	\$73,062	\$44,132	\$19,034
74								
75	FC	UTILITY	\$87,746	\$7,033	\$23,286	\$7,124	\$4,238	\$1,730
76	FC	COMMUNICATIONS	215,957	11,951	55,814	12,051	6,215	2,365
77		TOTAL	\$303,703	\$18,984	\$79,100	\$19,175	\$10,453	\$4,095
78								
79		DEPREC - REV EQUIP	\$527,563	\$46,718	\$215,213	\$79,974	\$67,392	\$16,607
80		OTHER DEPRECIATION	179,807	9,107	38,189	3,350	6,924	2,108
81		TOTAL DEPRECIATION	\$707,372	\$55,825	\$253,402	\$83,324	\$74,316	\$18,715
82								
83	VC	VEHICLE RENTS W/DRIVER	\$1,367,295	\$223,845	\$1,726,234	\$330,229	\$115,493	\$86,344
84	VC	VEHICLE RENTS W/O DRIVER	461,660	58,894	466,821	79,834	27,073	22,621
85		TRANSPN FM OTHER CARRIER	545,310	44,737	59,537	34,214	3,054	4,969
86		SHIPPER ALLOW/EQUIP RENT	10,705	(1,073)	(14,028)	(1,401)	(685)	(451)
87		TOTAL	\$2,384,970	\$326,403	\$1,838,564	\$462,876	\$144,935	\$113,483
88								
89	FC	BLDG/OFF EQUIP RENTS	\$176,905	\$12,879	\$39,802	\$11,307	\$3,902	\$3,050
90								
91		DISP OF OPER ASSETS - NET	(\$23,026)	(\$3,071)	(\$24,279)	(\$8,006)	(\$2,201)	(\$1,760)
92								
93	FC	MISC EXPENSES	\$154,049	\$10,355	\$54,910	\$14,310	\$11,263	\$2,784
94								
95		LINEHAUL	\$6,904,409	\$667,300	\$4,225,797	\$1,144,303	\$794,223	\$294,166
96		PU AND D	3,544,316	196,893	121,000	40,869	1,784	17,188
97		BILLING AND COLL	357,823	19,801	18,485	8,306	1,537	2,067
98		PLATFORM	2,184,245	31,622	19,212	3,832	2,315	986
99		TERMINAL	1,246,461	36,373	179,175	19,955	86,998	6,467
100		MAINTENANCE	282,053	28,946	138,025	40,717	64,277	12,066
101		TRAFFIC AND SALES	715,007	37,854	96,751	28,013	4,424	3,034
102		INSURANCE AND SAFETY	172,606	14,603	54,185	11,936	9,027	4,833
103		G AND A	835,121	91,089	375,048	103,250	51,510	24,987
104		TOTALS	\$16,242,043	\$1,124,481	\$5,227,678	\$1,401,181	\$1,016,095	\$365,794
105								
106		INTERCITY REVENUE	\$16,909,890	\$1,079,807	\$5,224,954	\$1,335,852	\$950,278	\$355,386

TABLE 33 (CONTINUED)

ALL DOLLAR FIGURES/MILEAGE IN 000's

LINE NR.	COST CAT.	ITEM	GENERAL FREIGHT		SPECIALIZED COMMON OTHER THAN GEN FRT		CONTRACT SPECIAL COMMODITY	
			CLASS I	CLASS II	CLASS I	CLASS II	CLASS I	CLASS II
109		MILES-OWNED VEH	4,493,300	396,797	1,603,921	549,685	447,110	138,786
110		MILES-RENTED W/ DRIVER	1,502,616	273,956	1,550,931	370,828	94,816	94,372
111		MILES-RENTED W/O DRIVER	761,954	104,039	650,778	99,335	60,400	51,063
112		TOTAL MILES DRIVEN	6,757,976	777,892	3,823,217	1,019,881	602,646	284,221
113								
114		TON MILES HWY SERVICE	87,123,079	9,109,702	53,432,514	14,866,022	7,054,568	4,534,091
115								
116		TONS COMMON CARRIER SERV	156,690	45,190	216,359	89,257	13,150	12,053
117								
118		REVENUE PER MILE	\$2.50	\$1.39	\$1.37	\$1.31	\$1.56	\$1.25
119		REV PER TON MILE, CENTS	18.90	11.85	9.77	8.98	12.80	7.83
120		REVENUE PER TON	\$107.27	\$23.88	\$23.89	\$14.95	\$43.52	\$21.03
121		AVG LOAD, TONS	12.89	11.71	13.98	14.58	11.71	15.95
122		AVERAGE HAUL, MILES	567.68	201.45	244.55	166.48	340.07	268.40

## FIXED AND VARIABLE COST MODEL

LINE NR.	ITEM	GENERAL FREIGHT		SPECIALIZED COMMON OTHER THAN GEN FRT		CONTRACT SPECIAL COMMODITY	
		CLASS I	CLASS II	CLASS I	CLASS II	CLASS I	CLASS II
123							
124							
125							
126							
127							
128							
129							
130							
131							
132							
133	FIXED COSTS:						
134							
135	SALARIES - OFF AND SUPER	\$1,500,794	\$62,827	\$238,422	\$63,231	\$40,607	\$15,716
136	CLERICAL AND ADMIN	604,132	37,056	96,229	30,843	22,091	6,637
137	OTHER	842,677	14,187	(16,706)	661	792	(398)
138	PRO RATED FC OF TIME OFF	147,538	2,354	4,974	821	2,594	223
139	PRO RATED FC OF FRINGES	555,350	14,907	28,159	9,164	8,688	1,878
140	TOT GEN OP SUPPLY AND EXP	791,465	48,022	196,377	42,226	49,722	9,520
141	OTHER TAX AND LIC	77,086	4,920	17,641	6,034	3,555	1,437
142	LIC AND REG FEES	204,944	17,024	90,085	25,905	22,054	5,873
143	OTHER INSURANCE	23,954	5,003	5,949	5,510	4,365	928
144	PL & PD	230,252	31,215	177,231	50,097	22,883	13,166
145	CARGO LOSS AND DAMAGE	205,355	7,690	51,680	8,772	15,054	1,928
146	FIRE, THEFT, COLL	21,403	5,851	18,018	8,683	1,830	3,012
147	UTILITY	87,746	7,033	23,286	7,124	4,238	1,730
148	COMMUNICATIONS	215,957	11,951	55,814	12,051	6,215	2,365
149	BLDG/OFF EQUIP RENTS	176,905	12,879	39,802	11,307	3,902	3,050
150	MISC EXPENSES	154,049	10,355	54,910	14,310	11,263	2,784
151							
152	TOTAL FIXED COSTS	\$5,839,807	\$293,275	\$1,081,871	\$296,739	\$219,853	\$69,849
153							

TABLE 33 (CONTINUED)

FIXED AND VARIABLE COST MODEL (CONTINUED)

ALL DOLLAR FIGURES/MILEAGE IN 000's

LINE NR.	COST CAT.	ITEM	GENERAL FREIGHT		SPECIALIZED COMMON OTHER THAN GEN FRT		CONTRACT SPECIAL COMMODITY	
			CLASS I	CLASS II	CLASS I	CLASS II	CLASS I	CLASS II
VARIABLE COSTS:								
155		DRIVERS/HELPERS	\$3,314,134	\$184,420	\$744,732	\$205,702	\$236,122	\$63,751
156		OWNER-OPERATOR	68,949	7,419	57,243	4,243	2,971	969
157		VEH REPAIR/SERVICE	328,775	20,029	123,013	31,024	32,788	8,733
158		PRO RATED VC OF TIME OFF	378,515	9,735	57,852	6,281	30,824	2,624
159		PRO RATED VC OF FRINGES	1,424,778	61,636	327,540	70,094	103,222	22,112
160		OTHER OP SUPPLIES/EXP	296,316	17,036	131,563	28,977	25,648	8,275
161		FUEL- MV	605,000	68,357	249,482	93,771	67,368	26,477
162		OIL, LUBE, COOLANTS	24,177	1,974	10,357	2,666	1,906	576
163		VEHICLE PARTS	243,191	29,730	120,354	51,756	25,633	11,360
164		VEH MAINT/OUT SIDE REP	186,786	12,932	71,297	16,947	15,127	5,343
165		TIRES AND TUBES	177,162	17,480	84,185	24,938	18,998	6,489
166		POL ST AND FED	285,135	21,300	100,102	29,849	18,583	8,795
167		VEHICLE RENTS W/DRIVER	1,367,295	223,845	1,326,234	350,229	115,493	86,344
168		VEHICLE RENTS W/O DRIVER	461,660	58,894	466,821	79,834	27,073	22,621
169								
170		TOTAL VARIABLE COSTS	\$9,161,873	\$734,786	\$3,871,175	\$996,311	\$721,756	\$274,469
171								
172								
173		CHECK FIGURES WITH ATA:						
174								
175		TFC	\$5,839,907	\$293,275	\$1,081,871	\$296,739	\$219,853	\$69,849
176		TVC	9,161,873	734,786	3,871,175	996,311	721,756	274,469
177		DEPN	707,372	55,825	253,402	83,324	74,316	18,715
178		DISP OF ASSETS	(23,026)	(3,071)	(24,279)	(8,006)	(2,201)	(1,760)
179		XPD FM OTH CARRIER	545,310	44,737	59,537	34,214	3,054	4,969
180		SHIPPERS ALLOW/RENT (CREDIT)	10,705	(1,073)	(14,028)	(1,401)	(685)	(451)
181								
182		TOTAL	\$16,242,041	\$1,124,479	\$5,227,678	\$1,401,181	\$1,016,093	\$365,791
183								
184		ATA	\$16,242,043	\$1,124,480	\$5,227,677	\$1,401,180	\$1,016,094	\$365,794
185								
186		DIFFERENCE FROM ROUNDING	(\$2)	(\$1)	\$1	\$1	(\$1)	(\$3)
187								

TABLE 33 (CONTINUED)

		COST CALCULATIONS					
		GENERAL FREIGHT		SPECIALIZED COMMON OTHER THAN GEN FRT		CONTRACT SPECIAL COMMODITY	
ITEM		CLASS I	CLASS II	CLASS I	CLASS II	CLASS I	CLASS II
199	TOTAL OPERATING REVENUE / MILE	\$2,543	\$1,512	\$1,421	\$1,424	\$1,812	\$1,331
200	(LINE 16/LINE 112)						
201	TOTAL OPERATING REVENUE/INTERCITY	\$2,502	\$1,388	\$1,367	\$1,310	\$1,577	\$1,250
202	(LINE 106/LINE 112)						
203	TOTAL OPERATING REVENUE/PMR UNIT	\$145,379	\$90,402	\$100,912	\$95,287	\$111,275	\$95,069
204	(LINE 16/LINE 22)*1K						
205	TOTAL OPERATING REVENUE/INTERCITY						
206	PER POWER UNIT OPERATED	\$143,050	\$83,011	\$97,055	\$87,631	\$96,819	\$89,315
207	(LINE 106/LINE 22)*1K						
208							
209							
210							
211	FC / VC MODEL:						
212							
213	TOTAL FIXED COSTS	\$5,839,807	\$293,275	\$1,081,871	\$296,739	\$219,853	\$69,849
214	(LINE 152)						
215	TOTAL VARIABLE COSTS	\$9,161,873	\$734,786	\$3,871,175	\$996,311	\$721,756	\$274,469
216	(LINE 170)						
217	TOTAL VARIABLE AND FIXED COSTS	\$15,001,680	\$1,028,061	\$4,953,046	\$1,293,050	\$941,609	\$344,318
218	(LINE 213+LINE 215)						
219	TOTAL MILES HIGHWAY SERVICE	\$6,757,976	\$777,892	\$3,823,217	\$1,019,881	\$602,646	\$284,221
220	(LINE 112)						
221	VARIABLE COST PER MILE	\$1,356	\$0,945	\$1,013	\$0,977	\$1,198	\$0,966
222	(LINE 215/LINE 219)						
223							
224							
225	CONTRIBUTION MARGIN/INTERCITY MIL	\$1,146	\$0,444	\$0,354	\$0,333	\$0,379	\$0,285
226	(LINE 201-LINE 221)						
227							
228							
229	OPERATING PROFIT	\$1,908,210	\$51,746	\$271,908	\$42,802	\$8,669	\$11,068
230	(LINE 106 - LINE 217)						
231	OPERATING PROFIT/MILE	28.236%	6.652%	7.112%	4.197%	1.438%	3.894%
232	(LINE 229/LINE 112)						
233							

TABLE 33 (CONTINUED)

		GENERAL FREIGHT		SPECIALIZED COMMON OTHER THAN GEN FRT		CONTRACT SPECIAL COMMODITY	
ITEM		CLASS I	CLASS II	CLASS I	CLASS II	CLASS I	CLASS II
236	TOTAL POWER UNITS OPERATED	118,210	13,008	53,835	15,244	9,815	3,979
237	TOTAL NUMBER OF FIRMS IN SURVEY	266	261	250	326	22	93
238	AVG NR. POWER UNITS PER FIRM	444	50	215	47	446	43
239	AVERAGE MILES / POWER UNIT (LINE 219/LINE 236)*1K	57,169	59,801	71,017	66,904	61,401	71,430
240	AVERAGE MILES / PER OWNED P. U. (LINE 109/LINE 23)*1K	50,310	49,048	67,380	61,860	55,854	65,465
241							
242	AVERAGE MILES RENTED/W DRIVER (LINE 110/LINE 24)*1K	89,977	80,268	79,279	73,286	114,512	76,045
243							
244	AVERAGE MILES RENTED W/O DRIVER (LINE 111/LINE 25)*1K	62,471	69,129	62,168	76,545	61,507	82,626
245							
246							
247							
248							
249	VARIABLE COSTS / POWER UNIT (LINE 215/LINE 236)*1K	\$77,505	\$56,487	\$71,908	\$65,358	\$73,536	\$68,979
250							
251							
252							
253	TOTAL COMMUNICATIONS EXPENSE	\$215,957	\$11,951	\$55,814	\$12,051	\$6,215	\$2,365
254							
255	COM EXP / POWER UNIT (LINE 76/LINE 22)*1K	\$1,827	\$919	\$2,345	\$1,356	\$776	\$1,116
256							
257						\$779	\$1,053
258	COM EXP / OWNED POWER UNIT (LINE 76/LINE 23)*1K	\$2,418	\$1,477	\$2,299	\$1,290		
259							
260							
261							
262							
263	VARIABLE COST / MILE FROM CATEGORY BREAKDOWN (LINE 95/LINE 112)	\$1.022	\$0.858	\$1.105	\$1.122	\$1.318	\$1.035
264							



#### LIST OF REFERENCES

1. Miller, A. C., Mobile Communication Alternatives for the Trucking Industry, proprietary report, 1988.
2. ECOSystems International, Inc., Land Mobile Market Integration Study, by H. L. Loats, C. F. Sauer, P. A. Castruio, 1980.
3. Second Report and Order, FCC 86-209, 104 FCC 2d, p. 654, 22 April 1986.
4. Whitford, R. K., "Aspects of Freight Service Quality for Just-in-Time Transportation Serving the U.S. Automobile Industry," Just-in-Time Transport: New Road Freight Transport Strategies and Management: Adapting to the New Requirements of Transport Services, Part 1, proceedings of a research seminar arranged by OECD and VTI, Svenska Massan, Gothenburg, 22-24 June 1987.
5. Beniger, H., The Control Revolution, p. 436, Harvard Press, 1986.
6. Order and Authorization, FCC 89-142, 4 FCC Record Nr. 11, pp. 4538-4541, 1989.
7. Memorandum Opinion, Order and Authorization, FCC 89-24, 1989.
8. Rothblatt, M. A., Radiodetermination Satellite Services and Standards, Artech House, Inc., 1987.
9. Qualcomm, Inc., "EUTELSAT and Qualcomm Team Up to Offer OmniTRACS In Europe," Transportation Times, pp. 4-5, Nr. 8910, Fall 1989.
10. Stoddard, R., "American Mobile Satellite Gears Up," Communications, October 1989.
11. Federal Communications Commission, FCC 89-183, adopted 31 May 1989, pp. 6-7.
12. AMSC press release dated 31 May 1989.
13. AMSC, Joint Amendment to the FCC, 1 February 1988.

14. Mobile Satellite Services, L.P., Application for a Mobile Satellite System, 4 September 1987 (subsequently became AMSC).
15. Phillips Publishing, Industrial Communications News Letter, Nr. 7, 17 February 1989.
16. American Radio Relay League, The ARRL Handbook For the Radio Amateur, 65th ed., Newington, Ct, 1988.
17. Shosteck, H., "Can Cellular Be Sold?," Telephone Engineer and Management, 15 July 1987.
18. Official Cellular Radio Handbook, Cellular Directions, 1988.
19. Hand transcribed from Cellular Telephone Service Areas Map, Cellular Directions, 5th edition, 1988.
20. Herschel Shosteck Associates Quarterly Survey, Data Flash Retail Market For Cellular Telephones, Vol. 6, Nr. 1, May 1989.
21. Lopez, J. A., "Once High-Tech Toys, Cellular Telephones Are Becoming Staples," Wall Street Journal, Vol. 71 Nr. 29, 11 August 1989.
22. Herschel Shosteck Associates Quarterly Survey, Data Flash Cellular Subscribers and Forecasts, Vol. 4, Nr. 1, May 1989.
23. Hellyer Communications Marketing Literature, 1989.
24. Herschel Shosteck Associates, The Demand For Cellular Telephone: 1995, Presentation Notes for the Ritzel/Phillips Cellular Seminar, Washington, D.C., 9 June 1988.
25. Mansfield, E., Microeconomic: Theory and Applications, W. W. Norton and Company, 1985.
26. Shosteck, H., "Will Cellular be a Viable Product in Small Markets?," Personal Communications Technology, reprint from the January 1986 edition.
27. "Mobility From Mercedes," Transat, Nr. 5, p. 14, February 1990.
28. E. F. Johnson Company, Clearchannel Ltr Application Note, pp. 1-1 to 1-4, October 1988.

29. Consumer Assistance and Small Business Division, Federal Communications Commission, "Specialized Mobile Radio System (SMRS)," fact sheet, February 1989.
30. General Electric Company, "Improve Your Business With Trunked Two-Way Radio," marketing fact sheet, undated.
31. Motorola Communications and Electronics, Sales force "presell" and other marketing literature, 1989.
32. Ardis Corp. press releases and marketing literature, April 1990.
33. Ericsson marketing literature, 1990.
34. Engle, J. and Thro, S., "Frequency Reuse Boosts RF/Data Terminal Throughput," Mobile Radio Technology, Vol. 3, February 1985.
35. Krebs, J., "Portable Computer and Host Talk Over Radio-frequency Link," Electronics, pp. 142-145, August 25, 1985.
36. Hennessee, J., "FCC Denies Petitions for Reconsideration in 87-14; Reaffirms Reallocation," QST, p. 50, October 1989.
37. Metrocast marketing literature, 1989.
38. Kirvan, P., "Radio Paging Still Hot," Communications News, Vol. 26, Nr. 8, August 1989.
39. Schrader, R., Electronic Communication, 4th ed., McGraw-Hill, 1980.
40. Friedman, H., "A National Radio Paging System," Radio Electronics, Vol. 59, Nr. 1, pp. 41-44, January 1988.
41. Map hand transcribed from Cue marketing literature dated October 1988.
42. National Satellite Paging marketing literature, 1989.
43. Carpenter, P., "Global Paging Means Never Being Out of Touch," paper presented at the INMARSAT Conference on Mobile Communications, London, Summer 1989.
44. AT&T 800 service rate tables dated 1 January 1988.

45. Furman, P., "Surface Transportation," Forbes, pp. 210-211, 12 January 1987.
46. Department of the Treasury, Internal Revenue Service, Publication 534, Depreciation, pp. 1-7, 98-106, Government Printing Office, December 1987.
47. Sassone, P. and Shaffer, W., Cost-Benefit Analysis, Academi Press, Inc., 1978.
48. American Trucking Associations, 1986 Motor Carrier Annual Report, Results of Operations Class I and II Motor Carriers of Property Regulated by the Interstate Commerce Commission, 1987.
49. The Marketing Research Bureau, Inc., The Truck Transportation Market - Communication and Positioning Systems, Published by the Management Systems Department, American Trucking Associations, 1985.
50. Ernst and Whinney Transportation and Logistics Group, Geostar Benefits Survey Frederick Transport, November 1988.
51. Ernst and Whinney Transportation and Logistics Group, Cost-Benefit Analysis of Geostar System 2C For KLLM Transport, February 1989.
52. Morgan, W. and Gordon, G., Communications Satellite Handbook, John Wiley and Sons, 1989.
53. Ford Aerospace Corp., A Program to Calculate Mobile Satellite Revenue, by Mr. Al McCracken, 1988, (Lotus 123 spreadsheet with graphics).
54. Attachment A to Omninet RDSS proposal, April 1985.
55. Magnavox Advanced Products and Systems Company to Omninet Corp., Subject: MSS Mobile Terminal Design and Production Cost Estimates, 18 March 1985.
56. U. S. Department of Commerce, Space Commerce: An Industry Assessment, p. 47, Government Printing Office, 1988.
57. Notice of Proposed Rule Making, General Docket 90-56, FCC 90-63, 1990.
58. Geostar Messaging Corporation, Petition for Rulemaking to Establish a Digital Land Mobile Satellite Service, RM-6459, 16 June 1989.

59. Geostar RDSS proposal, Attachment 3, 28 September 1984.
60. Waters Information Services, Fleet Management for the 90's: Opportunities for Mobile Computing in the Trucking Industry, Binghampton, N.Y., 1989.
61. Lundberg, O., Satellites and Their Role in the Mobile Revolution, text from a speech presented to the Financial Times Conference on the Outlook for World Mobile Communications, London, 8 November 1988.
62. EFC Satellite Services letter to the author, Subject: Forecast C and Ku-band Transponder Supply and Demand, 29 September 1989.
63. Lundberg, O., Mobile Satellite Services: The Main Issues, text from a speech presented at Asia Telecom, Singapore, 22 February 1989.
64. Locstar marketing literature, 1989.
65. Freibaum, J., The Mobile Satellite Service Conflicts and Potential Barriers to Growth, paper presented at the Mobile Satellite - Onward and Upward Conference, Washington, D.C., 6 November 1989.
66. International Telecommunications Union, Radio Regulations, 1982.
67. Gallagher, B., and others, Never Beyond Reach, International Maritime Satellite Organization, London, 1989.
68. O'Neill, L., and Snively, L., "The Geostar Position Determination and Digital Message System," IEEE 1983 National Telesystems Conference, pp. 312-314, IEEE, 1983.
69. Second Report and Order, General Docket Nr. 84-689, FCC 86-209, 104 FCC 2d, 1986.
70. Report and Order, General Docket Nrs. 84-1231, 84-1233, 84-1234, FCC 86-333, 2 FCC Record, Vol. 6, 1986.
71. Memorandum Opinion, Order and Authorization, General Docket Nr. 84-1234, FCC 89-183, 1989.
72. Second Report and Order, General Docket Nr. 84-1234, FCC 86-552, 2 FCC Record, 1987.

73. Report of the United States Delegation, ITU World Administrative Radio Conference for the Mobile Services, D. J. Markey, 23 December 1987.
74. Bulloch, C., "What Happened at WARC-MOB '87," Space Markets, v. 4/87, pp. 211-213, Winter 1987.
75. International Telecommunications Union, Final Acts of the World Administrative Radio Conference for the Mobile Services (MOB-87), Addendum, Geneva, 1987.
76. FCC news release, "Policy Adopted for Provision of INMARSAT Aeronautical Services to the U.S. (CC Docket 87-75), 31 May 1989.
77. Orbital Communications Corporation, Petition For Rulemaking, 28 February 1990.
78. Orbital Communications Corporation, Application For Authority to Construct a Low-Orbit Mobile Satellite System, 28 February 1990.
79. International Maritime Satellite Organization, Annual Review 1988-89, London, 1989.
80. International Maritime Satellite Organization, Basic Documents, 3rd ed., London, 1986.
81. INMARSAT letter to the author, Subject: Amendments to the INMARSAT Convention, 27 May 1989.
82. International Maritime Satellite Organization, The Standard-C Communication System, by N. Teller, L. Phillips, and C. Howard, undated.
83. International Maritime Satellite Organization, Mobile Satellite Communications Brought Down To Earth, by J. Bell, undated.
84. International Maritime Satellite Organization, The INMARSAT Standard-C Communications System, by K. Phillips, undated.
85. Thrane and Thrane A/S Telecommunications Engineering Standard-C marketing literature, 1989.
86. Kinal, G., Current Developments in the INMARSAT Radio Determination Program, paper presented at the 1989 Annual Assembly Meeting of the Radio Technical Commission for Maritime Services, Seattle, Wa., 9-13 April 1989.

87. Lundberg, O., On Competition, text from a speech presented at the International Space Communications and Technology Summit Conference, Washington, D.C., 14 September 1987.
88. Rothblatt, M., The Benefits of Satellite Services to the Land Transportation Industry, paper presented at Communication Networks Conference and Exposition, Washington, D.C., 27 January 1988.
89. Cheston, T., The Geostar Radiodetermination Satellite System: A Global Perspective, paper presented at the 1987 Annual Assembly Meeting of the Radio Technical Commission for Maritime Services, San Francisco, Ca., conference date unavailable.
90. Briskman, R., Geostar Initial RDSS System, unpublished paper, 8 November 1987.
91. Stoddard, R., "Geostar: RDSS on the Move," Satellite Communications, v. 10, nr. 11, pp. 22-24, October 1986.
92. Phillips Publishing, Inc., "Satellite Circuit," Satellite News, v. 13, nr. 12, p. 8, 12 March 1990.
93. Phillips Publishing, Inc., "Mobile Satellite," Satellite News, v.13, nr. 20, p. 8, 21 May 1990.
94. Antonio, F., and others, "Technical Characteristics of the OmniTRACS - The First Operational Mobile Ku-Band Satellite Communications System," Proceedings of the Mobile Satellite Conference, JPL Publication 88-9, Pasadena, Ca, 3-5 May 1988.
95. Jacobs, I., An Overview of the OmniTRACS: The First Operational Two-way Mobile Ku-Band Satellite Communication System, paper presented at the INMARSAT Mobile Satellite Conference, London, July 1989.
96. Telesat Mobile Inc., FAX to the author, Subject: Phase 1 Mobile Data Service, 12 April 1990.
97. AMSC letter to the author, Subject: AMSC System Information and Licensing, 18 August 1989.
98. Carre, R., Mrayati, M., "Theoretical Studies on Speech Processing," Telecommunication Journal, v. 55, pp. 839-853, December 1988.

99. Jet Propulsion Laboratory Report JPL 400-276, NASA's Mobile Satellite Program: A Cooperative Endeavor With Industry, November 1985.
100. Jet Propulsion Laboratory Report JPL 88-12, MSAT-X Report 148, MSAT-X: A Technical Introduction and Status Report, by K. Dessouky and M. Sue, ch. 5, pp. 19-25, 15 April 1988.
101. Advanced Electronic Applications, Inc., Use Packet Radio Technology and Existing RF Voice Paths to Send Data or Written Communications, by J. Gates, undated.
102. Davidoff, M., The Satellite Experimenter's Handbook, American Radio Relay League, 1984.
103. Gagliardi, R., Satellite Communications, Wadsworth, 1984.
104. McElroy, H., and others, Space Science and Applications, pp. 201-204, IEEE Press, 1986.
105. Evans, B., "Towards the Intelligent Bird," International Journal of Satellite Communications, v. 3, pp. 203-213, 1985.
106. Fiore and Rosenberg, "Earth Satellite Systems," Navigation, Journal of The Institute of Navigation, v. 17, nr. 3, pp. 135-145, Fall 1970.
107. Briskin, R. and others, "Land Mobile Communications and Position Fixing Using Satellites," IEEE Transactions on Vehicular Technology, v. VT-28, nr. 3, pp. 153-165, August, 1979.
108. Wells, D. and others, Guide to GPS Positioning, Canadian GPS Associates, 1987.
109. Ott, L., "Starfix: Commercial Satellite Positioning," Navigation Into the 21st Century, IEEE Plans 88 Position and Navigation Symposium Record, pp. 8-12, 29 November 1988.
110. Department of Defense and Department of Transportation, DoD 4560.4 and DOT-TSC-RSPA-87-3, Federal Radionavigation Plan, 1986.
111. Stansell, T., "The Navy Navigation Satellite System: Description and Status," Navigation, Journal of The Institute of Navigation, v. 15, nr. 3, pp. 229-238, Summer 1968.



112. Danchik, R., "Navy Navigation Satellite System Status," Navigation Into the 21st Century, IEEE Plans 88 Position and Navigation Symposium Record, pp. 21-24, 29 November 1988.
113. Chappell, P., Doppler Satellite Navigation - History and Principles of Operation, paper presented at the Doppler Satellite Applications to Offshore Surveying and Positioning Seminar, Houston, Tx, 6 May 1977.
114. U.S. Naval Observatory Automated Data Service Electronic Bulletin Board, @GPSSY file, Com1 202-653-1079, A/V 294-1079, FTS 653-1079, 300 - 2400 baud, full duplex, even parity modem, 4 July 1990.
115. Wooden, W., Navstar Global Positioning System Overview, paper presented at PACON 84 - Pacific Conference on Marine Technology, Honolulu, Hi, 24-27 April 1984.
116. Curry, T., Cassidy, F., "Developing a Low-Cost GPS Receiver For Marine Applications," Navigation Into the 21st Century, IEEE Plans 88 Position and Navigation Symposium Record, pp. 492-493, 29 November 1988.
117. Mooney, F., "Terrestrial Evaluation of the GPS Standard Positioning Service," Navigation, Journal of The Institute of Navigation, v. 32, nr. 4, pp. 351-369, Winter 1985-1986.
118. Applied Sciences Associates, Inc., Loran-C Engineering Course Reference Manual, U.S. Coast Guard Academy, New London, Ct, January 1988.
119. Department of Transportation, U.S. Coast Guard, Loran-C User Handbook, 1980.
120. Heyes, D., "The Loran-C Midcontinent Expansion Project - A Status Report," Navigation Into the 21st Century, IEEE Plans 88 Position and Navigation Symposium Record, pp. 215-219, 29 November 1988.
121. Reid, F., "Travels With Loran-C," The Lowdown, Publication of the Longwave Club of America, pp. 16-18, May 1985.
122. U.S. Department of Commerce, National Technical Information Service, Report PB-258 251, Loran-C Conceptual Analysis, p. 37, July 1976.

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